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

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A project dissertation submitted in partial fulfilment of the requirements for the degree of

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ABSTRACT

Title:	Modelling the impact of priority infrastructure on the performance of minibus taxi services in Southern Africa
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The minibus taxi industry has grown from a modest provider of public transportation to the largest supplier to the urban public. Attempts have been made by government to regulate, integrate, and upgrade this sector but such efforts have been met with varying levels of success. Taxi drivers face immense pressure from passengers and the taxi industry to increase their performance which leads to hostile driving behaviour and often fatal accidents on the road. Transit priority measures, which are techniques used to reduce delays for buses or other forms of public transport on congested roads, have been used to advance the quality of service of buses and BRT vehicles but have not been extended to include the paratransit industry.

The purpose of the study is to quantify the economic impact that these forms of infrastructure would have on minibus taxi operators, passengers, and other road users. The various forms of infrastructure were modelled to represent conditions in various parts of the city where frequent stops to load and offload passengers take place. Four alternative service options to the traditional curb-side stop were identified which included a queue-jumping lane, a queue-bypass lane, a single lane pre-signal strategy, and a dedicated minibus taxi lane. Five analytical models were developed, based on macroscopic traffic flow theory, using Excel, to gain a strategic understanding of how the benefits and costs of the infrastructure vary with different traffic conditions.

It was observed that all the infrastructure alternatives result in a decrease in travel time, user cost, operating cost, and the total cost per trip for the minibus taxis. Pertaining to the car drivers, a decrease in travel time and total cost was observed because of the reduced delay due to taxi stops no longer impeding traffic. Environmentally, a reduction in harmful gas emissions was noted, particularly in the

case of the minibus taxis. The single lane pre-signal strategy and the queue-jumping lane fared the best out of the five options with the lowest travel times and overall cost per hour, resulting in a decrease in total hourly cost of 56%, which consists of construction cost, user cost, and operating cost.

A low-cost, commercially available drone was used to monitor the traffic behaviour of minibus taxis on a selected road segment in Pretoria in order to determine the applicability and suitability of the various infrastructure forms. It was observed that the drivers often try to cut corners and skip traffic to save time during peak traffic scenarios. In two cases driving patterns like the case modelled for the queue-jumping lane were displayed cutting time off the drivers' trip. It was also observed that there is a shortage of infrastructure for minibus taxi operators to pick up and drop off passengers often resulting in them making informal stops that cause congestion.

The time passengers save on their often-long travel distances would go a long way to redress the transportation injustices of the past. The monthly savings of over R32 000,00 per taxi driver in operating cost would serve as a subsidy to a public transportation industry currently operating unaided. It was concluded that implementing such significant changes in the public transport industry in South Africa would be equivalent to providing minibus taxi operators with much needed financial support.

DECLARATION

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LIST OF ABBREVIATIONS

BRT	Bus Rapid Transit
PUTCO	Public Utility Transport Corporation
SANTACO	South African National Taxi Council
IRT	Integrated Rapid Transit
LUTP	Lagos Urban Transport Project
LAMATA	Lagos Metropolitan Area Transport Authority
SACCO	Savings and Credit Cooperative
CBD	Central Business District
HOV	High Occupancy Vehicle
VTTS	Value of travel time savings

LIST OF SYMBOLS

T	Bus dwell time at bus stop
a_h	Consumed time of each passenger h for boarding
b_q	Consumed time of each passenger q for alighting
m	Number of boarding passengers
n	Number of alighting passengers
C_d	Time for opening and closing doors
T_s	Service time at the bus stop
T_d	Dwell time in and/or out of the bus stop
T_m	Time in which buses move in and out of the bus stop
t_{we}	Time in which buses wait to enter the bus stop
t_{wl}	Time in which buses wait to leave the bus stop
t_e	Time in which buses enter the bus stop
t_l	Time in which buses leave the bus stop
c_{VH}	Unit coefficient representing cost associated with vehicle-hours
c_{VD}	Unit coefficient representing cost associated with vehicle-distance
c_{FS}	Unit coefficient representing cost associated with fleet size
AC_T	Annualised total cost
AC_0	Annualised total cost with the omission of vehicle ownership cost
C_o	Vehicle operating cost
C_f	Fuel cost
C_t	Cost of tyres and other expendables
C_m	Cost of vehicle maintenance
C_{fm}	Cost of facility maintenance
C_a	Administrative costs
C_s	Supervision and control centre cost
$\overline{T_a^{ij}}$	Access/egress time

$\overline{L_i}$	Distance to the closest bus stop (km)
$\overline{L_j}$	Distance from the bus stop (km)
V_a	Access/egress speed (m/s)
$\overline{T_w^{ij}}$	Initial waiting time
k	0.5 (Buses arriving at evenly spaced intervals and passengers arriving randomly)
f_l	Line frequency
$\overline{T_v^{ij}}$	Waiting time for transfers
V	Speed of buses in motion on the trunk (t) or feeder (f)
t_{ba}^{l}	Time required for passengers to board and alight the bus on the trunk or feeder route
t_s	Extra time required to accelerate, decelerate, and open and close doors on the trunk or feeder route
n_l	Number of stops on the trunk or feeder route
$\tau_{ij}\Delta$	Transfer penalty
d_{avg}	Average delay per vehicle
r	Effective red time for a traffic movement in seconds
C	Cycle length in seconds
v	Arrival rate in vehicles/second
s	Departure rate in vehicles/second
a	Acceleration and deceleration rate

1 INTRODUCTION

1.1 BACKGROUND

The paratransit industry, also referred to as the minibus taxi industry, in South Africa has grown from a modest, small provider of public transport to the largest supplier 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 et al., 2017). It is necessary for governing entities in developing-world cities to appreciate paratransit services in that they provide much of the population with the essential service of mobility and to not merely view them as a necessary nuisance. Promoting the taxi industry has been found to hold many scientific, social, and political opportunities to those using the service

Although attempts have been made by government to regulate, upgrade, and integrate the paratransit sector into the formal sector, they have been met with resistance. Schalekamp and Behrens (2010) argue that the reason for this is that the processes that have been undertaken to incorporate the informal with the formal transport industry have been flawed and unless the current processes are earnestly reviewed, there is little chance for the formalisation of the paratransit industry to succeed. Schalekamp and Behrens suggested that structured and detailed negotiations will have to become the norm when engaging with the operator and companies and such negotiations will have to take place at a much more decentralised level.

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 et al., 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, is poorly enforced.

Transit priority measures are techniques that are used to reduce delays for buses on congested roads and include a variety of treatments which can range from modifying the signage and the phasing of the traffic signals to the addition of a dedicated lane for buses. The benefits to these measures include (CMNRC, 2005):

- Increased efficiency in the transit system,
- Reduced travel time,

- Improved reliability, and
- Increased comfort.

The study of transit priority measures mentioned, however, have not been applied to incorporate minibus taxis in nor has enough research been conducted to determine the efficiency of implementing such measures to benefit paratransit operators.

1.2 OBJECTIVES OF THE STUDY

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, other road users, and society at large.

1.3 SCOPE OF THE STUDY

The various types of transit priority measures were limited to taxi bays, queue-jumping lanes, queue-bypass lanes, pre-signal strategies, and a dedicated taxi lane and the models developed were limited to a single-lane corridor. The priority measures were only applied to intersections where minibus taxis would benefit from receiving a time advantage, that is, the cases where taxi operators deliberately make longer stops to wait for more passengers or decide to park their car to avoid unnecessary losses were considered to be the exception and not considered. Only selected field data was collected, with the objective of calibrating models that are representative of the road conditions at a single point in time. The deliverables gathered from the models were limited to the travel time, the hourly user cost, the hourly operating cost, the cost of the infrastructure, the fuel cost for a one-way trip, the emissions emitted on a one-way trip, and the total cost of travel per hour.

The purpose of the model developed was not to measure traffic impacts at a micro level but rather to develop a more strategic understanding of how the benefits and costs of the infrastructure vary with different traffic conditions. The approach used was analytical and meant to represent typical operating conditions for South African cities, rather than specific case studies.

1.4 METHODOLOGY

The study is broadly divided into two main sections that follow upon one another:

1.) After the identification of four appropriate priority infrastructure as determined from literature, theoretical macroscopic models were developed and implemented using Microsoft Excel as the main modelling tool to estimate the transit priority measures in terms of travel time savings, cost of travel, and construction cost. The models were designed against a desired set of inputs which included arrival and departure rate, corridor length, design period, design speed, cycle length, and number of passengers transported. The four priority infrastructure models were compared to the base case of a curb-side taxi stop that is commonly used.

2.) The model was calibrated using field data from an actual corridor to illustrate the applicability and improve the predicting ability. A sensitivity analysis was also conducted using the input variables around which there is the most uncertainly to determine their effect on the outputs of the model. The models were then be used to determine outputs such that the most optimal form of transit priority measures could be determined for an actual corridor.

1.5 ORGANISATION OF THE REPORT

The report will consist of the following chapters:

- Chapter 1 serves as the introduction to the dissertation, outlining the objectives, scope, methodology and organisation of the research project.
- Chapter 2 contains a discussion of literature related to the different transit preferential treatments, existing knowledge on the success of these methods when applied to buses or bus rapid transits, and how these infrastructure options can improve the informal transportation industry in South Africa.
- Chapter 3 provides the detailed development and calibration process of the models characterising the various transit priority measures. The models can then be used to measure the delays on a road under various traffic conditions.
- Chapter 4 considers the experimental process whereby appropriate analysis methods will be used to extract the necessary information from the models.

- Chapter 5 contains the observations made of minibus taxi driver behaviour using a commercially available drone.
- Chapter 6 concludes with a summary of the addressed research objectives as stated in Chapter 1. Recommendations on future research activities that can augment and elaborate on the results of the research is summarised.

2 LITERATURE REVIEW

This chapter presents a review of the literature pertaining to this study and assists in developing a comprehensive understanding of paratransit reform, the need for the paratransit industry in the South African context, and the challenges facing the paratransit industry. It then investigates various transit priority measures that can influence the travel time of public transport users, and the development of a public transportation network model.

2.1 A BRIEF HISTORY OF THE MINIBUS TAXI INDUSTRY

The emergence of the minibus taxi industry began in the 1960s as a result of the introduction of pass laws under the Apartheid regime: due to the black community being forcibly moved to the outskirts of the city, the need for an unscheduled transportation service arose (Barrett, 2003). At the time the industry was considered illegal due to being unregulated but a decade later taxi drivers found a loophole in the Road Transportation Act - since a vehicle carrying 10 passengers was classified as a bus, taxi drivers were able to apply for permits to operate a 10-seater minibus provided they leave one seat open. In the 1980s the taxi industry was legalised and recognised by the government although the number of permits that were issued were restricted. In the 90s the industry played a very important role by transporting passengers to the voting polls at no cost in South Africa's first democratic elections. During this time the 16-seater vehicle became the preferred and legislated vehicle type. Over the following 10 years the taxi industry transformation began which included the formation of the National Taxi Task Team, and the genesis of the Democratisation and Legislation processes. The National Land and Transportation Act would also bring about national operating licences that would replace the taxi permits previously used. In recent years, however, efforts have been made by national and provincial governments to regulate and formalise these services. (Automobile Association, 2013) (Department of Transport, 2013) (Department of Transport, 2015)

2.2 THE NEED FOR THE PARATRANSIT INDUSTRY

Train, bus, the recently implemented BRT, and the minibus taxi are the four main forms of public transport in South Africa of which the number of daily commuter trips are 800 000, 1 million, 120 000, and 15 million respectively (Department of Transport, 2017). The commuter rail industry and the bus services enjoy a government subsidy of 44% and 56% respectively whilst the taxi industry is commercially self-sustainable. The national passenger railway network consists of 3 100 km track and 500 stations, the public bus system is made up of 19 000 registered buses and 100 bus stations, and the BRT system consists of 700 buses and 150 stations. The minibus taxi industry far out-performs the other modes of public transportation both in terms of its size and distance travelled with 250 000 taxis, 2 600 taxi ranks, and 19 billion km travelled yearly (Department of Transport, 2017) .

The taxi industry is of great economic importance to the country: the total number of people directly employed by the minibus taxi sector amounts to 180 000 and a further 150 000 additional jobs are associated with the sector indirectly which includes motor manufacturing, maintenance, and provision of supplies (Barrett, 2003).

From the 68% of the population that uses public transport as their primary mode of transport to work, 67% use the minibus taxi, 20% take the bus, and 13% travel on a train (Department of Transport, 2013, 2015). The majority of public transport users are low-income earning individuals as 50% of South Africans who earn less than R3000 a month either walk or drive in a taxi. It is therefore clear that this mode of transport is a core enabler to the economy of the country and transforming this industry can lead to the creation of more jobs and increase and improve efficiencies in the network. Figure 2-1 illustrates the split trend in work trips made in South Africa between 1996 and 2013.

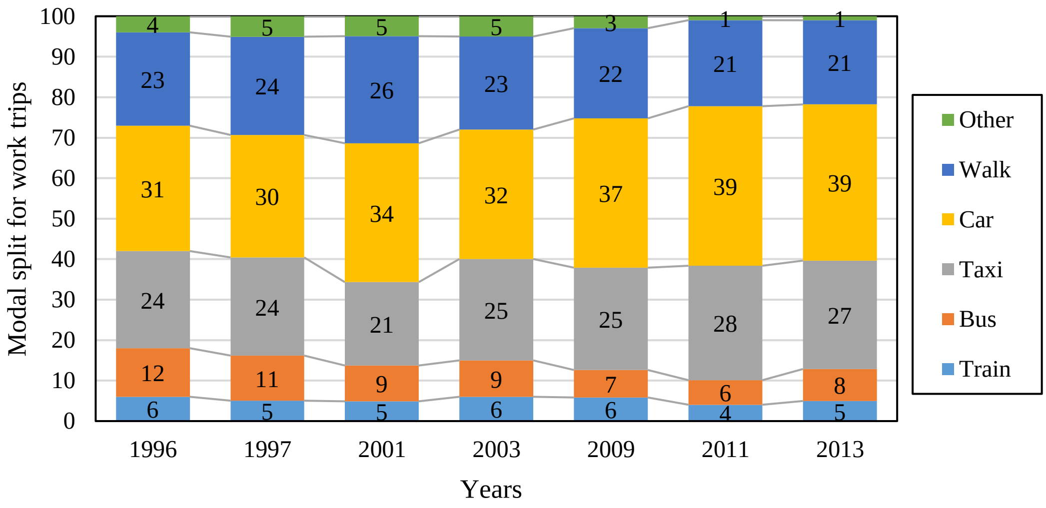


Figure 2-1: Graph of the modal split trend in South Africa (Department of Transport, 2013)

As illustrated in Figure 2-2, with the blue dots representing the stops made by minibus taxis in South Africa over a one-day period, the reach of the minibus taxi industry is extensive, and this provides commuters with a critical service by connecting them with important public transport nodes as depicted in Figure 2-3. Figure 2-3 also illustrates that the number of taxi-ranks far outnumber the number of bus and train stations and thus visually illustrating the popularity of this form of public transport.

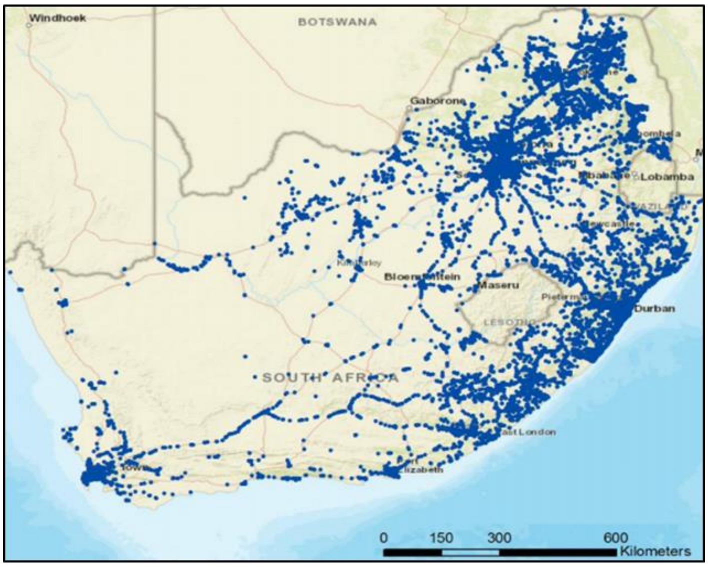


Figure 2-2: South African minibus taxi footprint (Transaction Capital, 2018)

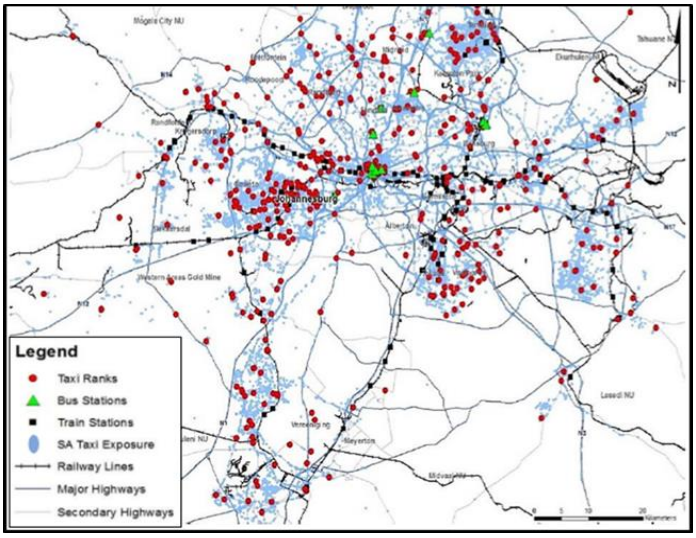


Figure 2-3: An integrated public transport network of Gauteng (Transaction Capital, 2018)

Attempts have been made to create more awareness and a better understanding with regard to the taxi industry in South Africa. An example of this is the documenting of the commuter taxi hand signs: Woolf (2013) published 26 taxi hand signs that are used in the greater Johannesburg area. This was done to assist commuters in navigating the taxi network. Figure 2-4 illustrates 8 examples of these hand signals. Many hand signals are geographically descriptive of a place, such as Figure 2-4b which is the hand signal used when a commuter wants to go to the township settlement Orance Farm, forming their hand in the shape of an absent orrange. In Figure 2-4c, the uneven ground in the area of Diepsloot is gesticulated by the rising and falling of the hand. To catch a taxi to the nearest T-junction, the shape of a T is made with two hands as illustrated in Figure 2-4c. The hand sign used by a commuter to go to town, us one finger pointing upwards (Figure 2-4e) and the sign to be transported to any nearby location is a downward pointing index finger tracing an imaginary circle (Figure 2-4f). By showing a downwards facing cupped hand (Figure 2-4d), the commuter is requesting transport to the nearest mall.

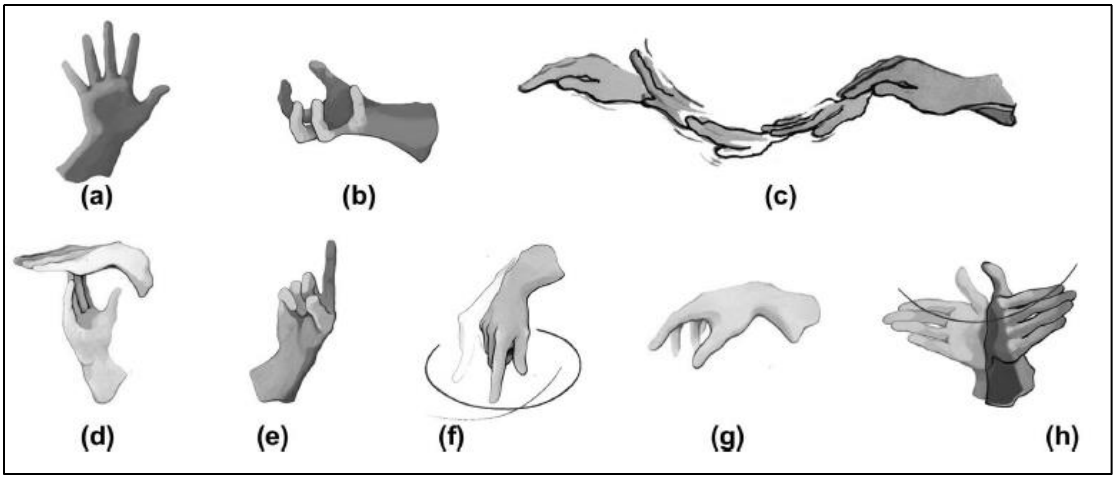


Figure 2-4: Selection of taxi hand signs (Woolf et al., 2013)

Traydon (2017) states in his column *"How giving way to minibus taxis serves the economy"* that minibus taxis are an integral part to South Africa's economy providing a cost-effective and convenient mode of transport to those that do not own a car. Taxis that transport up to 24 people should be viewed as commanding a higher priority on the road when compared to individuals traveling in their private vehicles. The reason for this opinion is that by giving way to a taxi driver, the speed and comfort of the passengers are improved and thus serving as an incentive for them to keep using the service. This, in turn, would keep the congestion on the roads from increasing.

2.3 THE CHALLENGES FACING THE PARATRANSIT INDUSTRY

There is great concern among road users in South Africa regarding road crashes in which minibus taxis are involved. Between the years 2013 and 2016 there have been a total of 648 fatal taxi crashes in Gauteng that have resulted in 857 deaths. The three main road user categories in which the fatalities occur are the passengers, the drivers, and pedestrians – almost the same number of pedestrians are killed as vehicle occupants. 43% of minibus taxi occupant fatalities occur in urban areas, followed by 32% on main arterials and 25% on freeways (Arrive Alive, 2016).

Govender and Allopi (2007) investigated the trends and factors causing the accidents and identified defective brakes and driver pressure as the two most significant. Minibus taxis, by virtue of being the most popular form of public transport in South Africa, are subjected to operating conditions far more severe to that of an ordinary passenger car. Operating at higher speeds to reduce travel time and overloading greatly increases the stopping distance which often results in fatal consequences. This issue gets compounded by the taxi driver having to meet strict daily requirements in terms of number of passengers transported and trips made. In the event of a brake pad or lining requiring replacement, the driver would make the cheapest purchase as this directly influences his wages. (Govender & Allopi, 2007)

The unlawfulness, aggressive and sometimes dangerous behaviour displayed by minibus taxi drivers also contribute to the accidents that they cause (Sinclair et al., 2015). This also adds to the dissatisfaction experienced by the mostly captive commuters. When compared to other drivers, taxi drivers display significantly higher levels of aggressive driving behaviour which include traffic obstructions, a disregard for traffic signs and signals, and improper passing behaviour. The most prevalent aggressive driving behaviour as experienced by other road users is when a taxi driver cuts in too close to the vehicle behind it. This all adds to the general negative light in which minibus taxis are viewed in South Africa.

Taxi violence is another cause for concern to the South African government: The Parliament's Police Portfolio Committee warned that the violence is currently at a crisis level (Jordaan, 2018). Disputes between taxi associations over service corridors often lead to violent confrontations which has resulted in the deaths of many taxi drivers and passengers. According to the committee chairperson, illegal firearms are used in most of the acts of violence.

Despite the growth that the industry saw over the past three decades, taxi operators still receive no formal training and do not enjoy any employment protection. There are two main models which are used to form the salary structure of a minibus taxi operator: in the first, and most common, the taxi owner specifies the daily amount that the driver has to make – this amount is based on the distance of the operating licence route of the vehicle (Woolf et al., 2013). From the total weekly earnings, the driver receives his salary which is typically 30% of the earnings. The money that the driver makes in excess of the specified amount is his to keep. In the second model, the owner will establish a weekly contract price. The driver will then spend the first part of the week working to achieve the contract price. The money the driver makes once the contract price has been reached is his income for the week.

All of the problems that minibus taxi operators face and the negative view that the public has towards them regarding traffic etiquette, safety, consideration, and following the rules of the road stem from the their need to survive financially which encompasses the frequency of their routes travelled, passenger capacity, and the number of passengers transported (Joubert et al., 2014). Government efforts in response to improving the operating conditions of the minibus taxi services in South Africa have taken many forms. The next section investigates the approaches that have been taken to reform this industry.

2.4 APPROACHES TO PARATRANSIT REFORM

There have been a range of approaches taken to reform paratransit industries from the renewal of a multi-modal public transport system to the introduction of a new transportation mode. Some of the methods that have been used include Bus Rapid Transit (BRT) and paratransit integration, stepped paratransit transition and upgrading, competition regulation through franchising or concessions, and existing service and regulatory improvements (Schalekamp et al., 2016).

With the integration of the BRT and paratransit industries, cities have attempted to move towards providing formal public transportation at a large scale. The advocates of this approach reason that if existing paratransit owners are assimilated into the BRT operating companies, they can enter into contracts that allow them to provide services as part of an integrated network.

Stepped paratransit transition and upgrading entails the transition to a high-quality bus transportation system that operates like a paratransit system. This approach is more flexible as it allows for greater engagements with the paratransit operators and they also have a way out of the process at multiple points. The programme comprises of five sequential steps of which the first consists of collective fleet management, where authorities support paratransit operators to form co-operatives with professional management that would operate their existing vehicles. The second step is to introduce a formal fare collection system. Thirdly, once cash and operations have been separated, paratransit vehicle ownership, where owners become shareholders in the company, can take place. The next step involves increasing the size of the fleet to meet the demand in the area and finally, once all this has been achieved, the new company would be given the opportunity to operate alongside existing formal bus operators.

The third reform approach, competition regulation through franchising or concessions, entails public authorities regulating competition between paratransit operators on an area-based level and not on a route level. Franchising or concession agreements between public authorities and paratransit associations can be used to monitor the service requirements of the paratransit operators and the operators are left to develop their routes amongst themselves.

Lastly, the improvement of existing services and regulations is an approach that does not attempt to fundamentally change the ownership of the paratransit sector or the way competition between paratransit operators is managed. The interventions undertaken by the public sector should rather be limited to issues that affect paratransit passengers' safety directly like enforcing vehicle roadworthiness standards and safe driving behaviour.

What follows is a study of the approaches various cities, namely, Johannesburg, Cape Town, Lagos, Santiago, Bogotá, and Nairobi took to reform and formalise their informal transportation industries.

2.4.1 Johannesburg – South Africa

Rea Vaya in Johannesburg is the first full BRT to be implemented in Africa, however the processes that had to take place before this project could be executed were extensive. The process started by participating in meetings with the two largest taxi organisations in Johannesburg – during the meetings great care was taken to ensure positive engagement. The two taxi organisations, Top Six and the Greater Johannesburg Regional Taxi Council, as well as the Public Utility Transport Corporation (PUTCO), Metrobus, the Johannesburg transport department and various politicians were invited on a study tour to Bogotá in Columbia (Allen, 2011). This was done so that the affected parties could gain a better understanding of a BRT system and the advantages it may hold for a large city as Johannesburg. Following the study tour, the minibus operators were offered to attend a series of workshops to explain how the system will be implemented and encourage them to cooperate with the new changes.

Before the implementation of the first phase, 1A, of the Rea Vaya system could commence, discussions between the City and the affected minibus taxi operator representatives took place. A preliminary agreement was reached as to which taxi routes would be affected and the number of taxis that should be removed from operation and in return the representatives would be offered participation in the BRT system (McCaul et al., 2011). It was decided that a total of 585 minibus taxis would be replaced with 143 BRT buses that would travel on the relinquished taxi routes, however, 650 taxis would continue to serve on the route as well. It is necessary to mention that the Pat Mbatha taxi-way, which was a taxi-only road connecting Soweto to the Johannesburg Central Business District (CBD), was one of the roads that was relinquished by the taxi association to the BRT route. It can thus be said that a form of paratransit priority infrastructure already existed before the construction of the Rea Vaya route which was lost in an attempt to make the city appear more world-class in preparation for the 2010 FIFA Football World Cup. Various other areas were targeted in the negotiation process, including (McCaul et al., 2011):

- Compensating minibus taxi operators for loss in income due to the rollout of Phase 1A of Rea Vaya,
- The fee per kilometre of each type of bus,
- Employment for taxi drivers that were displaced by the BRT system, and
- Compensation for operators who were unable to work due to intimidation arising from their participation in the negotiations.

Implementation of the BRT has taken place over three phases thus far: Phase 1A consisted of introducing a trunk route service between Thokoza Park in Soweto to Ellis Park Stadium. The route is 25,5 km in length and passes through a total of 33 stations. In Phase 1B, a route from Dobsonville, Soweto runs to Parktown, passing the Universities of Johannesburg and Witwatersrand. Finally, Phase 1C aims to introduce routes between Alexandra in the north and Cresta in the west (Rea Vaya Joburg, 2018). Each BRT bus has a capacity of between 90 and 112 passengers and are varied depending on the demand experienced.

According to Brendan Peterson, Rea Vaya’s finance and administration director, the system should be able to transport 102 000 people a day, however, only 35 000 commuters are making use of this service daily whereas the number of people making use of minibus taxis is still significantly greater (Venter, 2014). At the end of 2017, the Mayor of Johannesburg, Herman Mashaba suggested that the minibus taxis share the lanes that are dedicated for the buses (Dlamini, 2017). This suggestion was welcomed by the South African National Taxi Council (SANTACO) as the taxi operators felt that they are being left out of the city’s public transport plans. A limited mathematical study found, however, that this plan would slow down the average bus speed thus affecting the bus timetable due to the large increase in number of taxis on the dedicated bus lane (Fowkes et al., 2015).

Venter (2013) states that the transformational success of the minibus taxi system relies on three main points:

- The larger BRT vehicles, by virtue of accommodating more passengers, travelling at higher speeds, and ensuring more efficient labour practices, are able to reduce the operating costs which in turn reduces the ticket prices.
- The increased use of the BRT forces taxi drivers to venture out of their enclaves in which they offer their services to captured users – in so doing they are able to offer an alternative form of transport to car users.
- Finally, by government authorities ensuring that taxi drivers keep to their commitments pertaining to conflict resolution procedures, the BRT system can function relatively unhindered.

Venter (2012), however, concludes that keeping to these three points is improbable and unlikely which prevents BRT from transforming and formalising in South Africa and, in turn, prevents suitable integration between the BRT and minibus taxis.

2.4.2 Cape Town – South Africa

Prior to 2007 the City of Cape Town had a functioning public transportation system consisting of rail, minibus taxis, and buses, all privately owned, however, regulated by the national and provincial governments. Due to slow travel times, safety concerns, and poor image of the transportation systems, a significant number of people opted to travel with their privately-owned vehicles which increased the congestion on the streets. At the time when an alternative public transport system was considered, the modal split of inbound passenger trips to the city between 06h00 and 19h00 consisted of 67% cars, 17.2% rail, 11.4% minibus taxis, and 3.8% buses (Lewars et al., 2007).

The City of Cape Town started working on the first phase of the Integrated Rapid Transit (IRT) in 2007 and an emphasis was placed on the need for integration with other modes of transport (MyCiTi, 2018). The implementation has taken place over several phases: the first elements of the system had to be in place for the city to be ready to host the 2010 FIFA World Cup which consisted of a service providing tourists and sports enthusiasts transport to and from the Cape Town stadium, a service to the airport, and one around the inner city. In May 2011, the network was officially launched. In 2013 the service was extended to incorporate a route to the train station and since then subsequent routes have been added. A second, third, and fourth phase is in the pipeline and it is expected for the project to take another 20 years to reach completion. The final aim of the project is to build a reliable, safe, and cost-effective transport network and ensuring that, by the project’s completion, 75% of the homes in the city are within 500 m of a form of transport.

With the implementation of the MyCiTi transportation system in May 2010, a fleet of three vehicle types were chosen: 18 m articulated buses capable of accommodating 130 passengers, 12 m rigid buses, accommodating 85 passengers, and 9 m buses that can carry up to 50 passengers and are able to travel the narrow and steep roads in Cape Town efficiently (Bulman et al., 2014). The method of payment that is used across the MyCiTi transport modes is a “tapping on” and “tapping off” system with a card that is loaded with money. In August of 2013 a distance-based fare structure was launched. Attributable to the difficulties faced with compensating the affected minibus taxi drivers due to the new system, the City decided to partner with the taxi associations and bus companies who were, at the time, operating in the planned MyCiTi areas. Three companies, Table Bay Rapid Transit, Kidrogen, and TransPeninsula operate the service and assist in managing the bus companies, providing drivers, and providing technical and managerial support.

Many reviews and analyses have been carried out from the point of view of the transport authority or of that of the passenger. However, little analysis has been performed concerning the effect that the implementation of a BRT system would have on the minibus taxi operators with regard to their displacement (Del Mistro et al., 2015). A cost model was used to determine the benefits of having the minibus taxi drivers operate as a feeder system instead of a line haul public transport system. Figure 2-1 illustrates the change in structure.

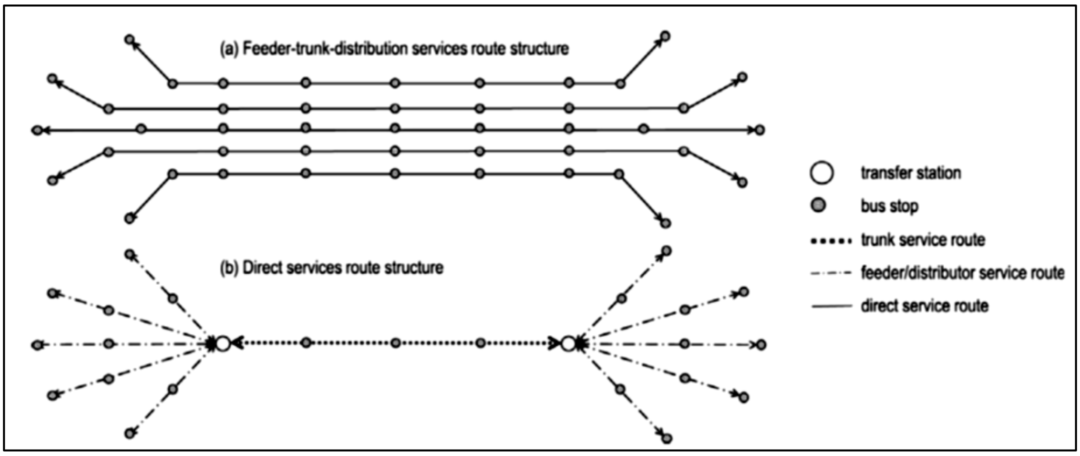


Figure 2-5: Route structures (Del Mistro et al., 2015)

The results from the model suggested that minibus operators would fare better if they only provided feeder or distribution services to the BRT system: from the two feeder-distributer options tested, namely 5 km and 10 km, the taxi industry would experience a decrease in travel per minibus of 23% and 15% respectively, a reduction in fare income of 17.1% and 8.8% respectively, and a reduction in operating costs of 38% and 20% respectively. All the reductions suggest that the operating efficiencies of the minibus taxi operator will improve; however, this will only be possible at the cost of reducing the size of the minibus fleet by 43% and 16.2% for the 5 km and 10 km options respectively. If a method such as this is implemented, the onus lies on the government to incorporate the minibus taxi drivers into the BRT system.

Often government entities in South Africa, as well as elsewhere in Sub-Saharan Africa, make decisions to reform their public transport systems, of which minibus taxis form a significant part, by replacing them and/or incorporating them into a proposed BRT system. This is done with risks involved: many cities have experienced strong resistance from the taxi operators, timeframes of implementation plans had to be extended, or projects sizes had to be reduced to save costs (Schalekamp, 2017). Working with the taxi operators and endeavouring to understand their attitudes to the reformation process as well as aiding them in skills development are some alternatives when undergoing reforms on such a large scale, especially when so many jobs are at stake. The City of Cape Town initiated a pre-emptive course aimed at supporting and training taxi operators before they would become involved in the reform and negotiation processes. This was the first of its kind in Africa and the result was more beneficial engagements between the minibus taxi corporations and the government.

2.4.3 Lagos – Nigeria

The birth of the BRT-Lite system in Lagos, Nigeria, was due to the challenging circumstances that the city faced: just behind Tokyo and Mumbai, Lagos would become the largest agglomeration in the world by the year 2025 with a population of 25 million. Before the implementation of the system, Lagos was the only megacity in the world without an organised transport system and residents had to rely on minibuses, known as danfo, midibuses, known as molue, and shared taxis, referred to as kabu-kabu, for their mobility. Commuters would utilise motor-cycle taxis, okada, for their local journeys. The problem with these modes, however, is that although they are widely used, they are not well-liked modes of transport – the journeys have been said to be unsafe and uncomfortable and the operators are often unfriendly. The drivers also favour short journeys to maximise their profits (Mobereola, 2009). Due to the danfo and molue being almost entirely privately owned, the fares differ greatly between drivers and the costs associated with using these transport modes account for as much as 20 percent of a typical passenger’s disposable income (World Bank Group, 2016). The quality of transport and the user costs involved were not the only reasons for renewing the public transport system in the city: high vehicle ownership combined with an inadequate road network caused a great deal of congestion on the roads. A journey from the residential areas to the north or west of the city could take up to two hours or even more in the case of vehicle accidents or flooding.

After conducting numerous studies, the Lagos Urban Transport Project (LUTP) began identifying priority actions that would need to be taken (Mobereola, 2009). The project took on a multi-modal transport approach consisting of rail, waterway mass transit, and road networks of which bus services would form the core component of the project. After an analysis it was found that that there was no mechanism that would oversee plans and actions of various agencies at the different levels of government. It thus became essential for the LUTP to create an authority that would act in a coordinating capacity. As a result, the Lagos Metropolitan Area Transport Authority (LAMATA) was established in 2002 to empower the authority. Due to the danfo and molue taking their fares and routing to the extremes to respond to demand, they decided to start exercising regulatory control: mini- and midi-bus drivers had to apply for route licenses on demand to ensure controlled competition. The first phase of the LUTP placed an emphasis on fast-return investments like road maintenance and road rehabilitation as well as improvements to junctions.

After consultation with the operator unions and associations, LAMATA agreed to provide an enabling framework which included workshops, traffic systems management measures, and passenger terminals and, in turn, the operators would agree to abide by the regulatory enforcement and commit to procuring larger buses. This would ensure fewer buses on the road, by accommodating more passengers, reduce congestion and potentially lower the fare costs (Mobereola, 2009).

The BRT-Lite system was implemented to improve mobility and transport affordability in the city. The first phase of the project consisted of a 22-km route that operated from 06h00 to 10h00 daily making use of 220 buses (Lagos Metropolitan Area Transport Authority, 2017). Five years after the implementation of the route, more than 400 million passengers had been moved by the system and it boasted of transporting 180 000 passengers daily. Due to the success of the BRT-Lite, there have been plans to extend the route to a further eight corridors in the metro.

2.4.4 Santiago – Chile

Santiago is made up of 37 municipalities and has a population of over 5 million. It is considered Chile’s most important city as it is the administrative and political centre of the country. The public transport system in Santiago has, over the past four decades, gone through numerous public transport policies: from strong regulation until 1979 with regard to fares, frequencies, and types of vehicles; to little control between 1980 and 1990 where the government encouraged a free-market approach which improved the frequency and coverage of the services but resulted in an excess in buses on the road; and after 1990 regulation was reintroduced by the government (Hidalgo et al., 2016; Figueroa, 2013).

The main idea behind Transantiago was to integrate the private bus system with the government owned metro (Schalekamp et al., 2009). A fleet of mostly new buses would replace all the existing paratransit vehicles in a day – this became known as the "Big Bang" approach. The routes were bundled together in trunk-and-feeder areas and foreign operators were employed to drive on the trunk routes.

The implementation of Transantiago started, in full scale, on Saturday the 10th of February 2007, albeit 5 months late, to allow for completion of the infrastructure and technological components of the system (Hidalgo et al., 2007). Through reducing the number of busses that operated, the congestion on the streets lessened and the city experienced a decrease in greenhouse gas emissions. The fare that was established was the same as that which was charged by the buses previously, but in the case of Transantiago, this included integration. This meant that users would experience lower travel costs as well as shorter trips with the new system. During the first weeks, however, many problems were realised: users had to walk long distances and wait longer due to the reduction in bus numbers, because of the lower bus frequency they were often overcrowded, poor transfer coordination due to a lack of understanding the system, inadequate facilities, and insufficient information provided to the users with regards to routes and frequencies. The "Big Bang" implementation approach was considered to be a failure since the trains became overcrowded due to few people making use of the buses. Although several years later, the integrated system is improving with total ridership increasing since the implementation of Transantiago.

An anonymous survey, consisting of 24 questions, was conducted to analyse the work situation as experienced by the drivers and considered possible measures suggested by the drivers that would improve the working conditions for the drivers as well as an increased level of service for the passengers. The results of the survey were summarised into four main points: incentives to improve performance, stressful situations for drivers, working conditions, and drivers' recommendations (Tiznado et al., 2014). Each point will be elaborated upon. In the case of incentives, 77% of the sample agreed that bonuses should be given if a certain level of service is achieved. 59%, however, did not agree that a part of their salary should be dependent on the passenger's view of the driver as a consensus amongst the drivers was that the passengers treat them poorly. In addition to disagreeing to being incentivised based on how the passengers rated the driver, 40% of the sample stated that the attitude of the passengers was a major factor when asked about stressful situations. Merely 5% mentioned congestion on the road as being significant and 14% commented on the tight schedules that must be maintained. When asked about their level of satisfaction with their employers and working conditions, although not evenly spread amongst the groups, 57% stated that they were satisfied with their employers. The reactions regarding working conditions were mixed depending on the group and varied between good and bad. Finally, the suggestions and recommendations from the drivers included better schedules (21%), better communications and more trust between bosses and employees (17%), higher salaries and bonuses (17%), more bus maintenance (14%), and more flexible holidays and rest days (10%).

A great gift that the Transantiago has provided academia is that of "Big Data" through automatically collected GPS and smart card data (Gschwender et al., 2016). The data obtained daily has given rise to significant achievements in research and teaching as well as providing savings in manual measures, and better quality of information obtained which in turn results in improved public policies pertaining to urban mobility.

A review was carried out regarding the state of the Transantiago system, 5 years after its launch. With regard to the public transport services that the system provides, the number of buses has been increased to accommodate all the passengers and to improve the level of service (Muñoz et al., 2014). The current fleet of buses was under constant renewal to replace the buses that operated in the previous system. Since the implementation of the new system, the percentage of buses that satisfied the EURO III environmental standard went from 53% in 2007 to 92% in May 2012. The structure, due to operating as a trunk-and-feeder system, intended to increase the number of trips with transfers from 10% with the previous system to 60% with the new system. However, the authorities aimed at reducing the number of transfers by joining and extending some services and reducing the exclusivity of the feeder zones and corridors – this would prove to be difficult due to the rigidity of the contracts which were only due to expire in 2012. Since the new system started functioning in 2007, the Metro saw an increase in riders due to the fare integration as well as the poor level of service experienced from the bus service. Since 2007, the fleet of train cars has been increased and a skip-stop operation was implemented which increased the capacity by 10%. The Metro has also extended its operating hours.

2.4.5 Bogotá – Colombia

The capital of Columbia, Bogotá, has an urban population of over 5 million. As of the year 1995, before the aggressive public transportation process was implemented, buses made up the most used mode of transport with 55.7% of the population using them to travel, followed by walking at 22.5%, and driving a car at 14.9% (Ardila et al., 2002). The transportation system that was in use before TransMilenio was implemented consisted of 15 000 buses owned by 66 different private companies as well as 50 000 taxis also owned by private companies (World

Bank, 2011). The system was dangerous, underused, and offering a low quality of service with no designated bus stops and payment was made in cash. An increase in the number of cars on the road over the past two decades caused the accident rates, commute times, and air pollution to increase (Turner et al., 2012).

Various projects were implemented to combat the increase in congestion in Bogotá: 344 km of bicycle lanes were constructed across the city, an annual Car Free Day is held city-wide on the first Thursday of every February, roadway restriction is enforced based on the vehicle's number-plate, and, the cornerstone of this effort, the TransMilenio Bus Rapid Transit system was implemented spanning a total distance of 87 km of trunk corridors (CCAP, 2012). The TransMilenio system, while combating congestion, also formed part of a 3-year multibillion-dollar refurbishment project. Other parts of the project included park refurbishments, paving of roads, and constructing new schools and libraries. The system makes use of a trunk and feeder system to provide the population of the city with mobility: the trunk consists of red articulated and biarticulated buses that can transport up to 160 and 250 passengers respectively (TransMilenio S.A., 2013). The route goes through the city's main roads connecting the stations and portals. The feeder service transports passengers to and from the surrounding stations and portals. The vehicles used are green buses that has a capacity of 90 people. The TransMilenio has an integrated payment method whereby the user can purchase and load money on a card that can be used on all the bus services.

The implementation of the system was not without its difficulties: loss of business, retiring existing operators, uncertainty whether the government would follow through with their plans of constructing infrastructure, and financial risk with investing in new buses were some of the causes of resistance from the bus operators (Turner et al., 2012). These obstacles were not insurmountable as city agencies employed different methods to incorporate the affected parties into the project. In the Terms of Reference, experience in public transportation in the city was included as a prerequisite to be included in the bidding process to become a stakeholder in the system. In the end a total of 59 companies became shareholders of the bidding companies. Extensive, open dialogues were also held to consider the relocation of routes and to negotiate the terms and conditions of the contracts.

To overcome the problem concerning the increased fares - ensuring that they were high enough so that no subsidies would be required and at the same time keeping it low enough to be affordable to low-income users – a fuel tax of 25% was introduced (Turner et al., 2012). This helped fund the TransMilenio and at the same time acting as a deterrent to those travelling by car and motivating them to make use of public transport.

What the TransMilenio did well were successful planning and implementation over a short period of time, distributing the responsibilities, incentives, and risks in the project development and operation phases adequately, bidding contracts were awarded and this competitive process was instrumental in ensuring regulation and control is exercised, the private operators were funded solely through the revenue they made through fares, and a high performance by the service itself (Hidalgo et al., 2007).

2.4.6 Nairobi - Kenya

The paratransit vehicles, known in Kenya as matatus, are the main provider of public transport services. Formal transport in Nairobi (commuter rail and former bus service), has not met the demands of the city and thus the country has seen an overall growth in this informal transport sector (Aduwo, 1990). Not only do the matatus provide convenient transport to an increasing number of the population, but the industry also provides many employment opportunities to those in the low-income bracket. Their rapid growth has unfortunately led to many accidents and other traffic management problems due to the lack of regulation by the government.

Aduwo also attempted to determine why users prefer the matatus over buses. He found that frequency of service and comfort were the two factors that were valued most highly whereas cost and safety were valued the least. The matatu users stated that they valued the availability of seats as well as room for their luggage. The frequent availability, flexibility, and faster travelling time were among the other reasons why users were willing to queue in line for a matatu. Although this research was carried out in 1990, nearly 30 years later this is still the case as the buses are said to be unreliable and have damaged bodies due to frequent accidents. Robberies and pickpockets are frequent on the buses and other discomforts include loud music being played, preachers shouting out sermons and hawkers selling goods (Livinginnairobi, 2012).

To make transport more accessible to the public cashless payments became mandatory for public transport services in 2014 (Jennings et al., 2017). The aim of this was to eliminate the amount of cash that the matatu drivers had to handle, and by extension this would reduce the number of bribes paid to the police by the matatu drivers. BuuPass was created after winning the 2016 Hult Prize (Nairobi Garage, 2018). BuuPass enables a user to book a bus or matatu trip online or with the use of a cell phone. No internet connection is required if a cell phone is used, the user simply must dial a short-code from an analogue or smartphone and proceed to select a vehicle, route, and arrival time. The process is completed by entering a pin, paying using their mobile account and showing the driver their confirmation number. The BuuPass website boasts about its benefits which include using the best bus companies, improved booking convenience, flexible methods of payments, and great customer care (BuuPass, 2018). Williams et al. (2015) suggested that there is a necessity to collect data from Nairobi’s semi-formal transportation system (i.e. the matatus). The data obtained could then be used for the development of more transportation applications which would then begin to solve the problem of congestion and lack of public transport for the poor.

In 2010 the public transport authorities in Kenya observed that some of the inner-city matatu businesses organising into Savings and Credit Cooperatives (SACCOs) resulting in an increase in the quality of service and regulatory compliance (Migwi, 2011). Due to the benefits that being a member of a SACCO had, not only for the operators but also for the passengers and the government, the Ministry of Transport and the Transport Licencing Board in 2010 made it compulsory for matatu businesses to either consolidate in a SACCO or a transport management company for their public service vehicle licence to be renewed. Organising the matatus in the inner-city of Nairobi was an important step in improving the quality of service. The SACCOs provide financing for the renewal, repair, and maintenance of a matatu and in some cases, they will take away incentives due to reckless driving (Behrens et al., 2017).

Despite the already congested roads, high air pollution, and transport delays, the population of Nairobi is still expected to rapidly increase – this will result in the damaging of the economy and the health of the public (Salon et al., 2012). It is estimated that two thirds of the city’s residents live below the poverty line which means that the poor are constrained in their options for transport since bicycles are not common in the city. The result of this is that those who cannot afford transport do not travel far from home or make short trips within the neighbourhood. The wealthier residents can afford safer, more comfortable, and more reliable forms of transport of which the majority choose to purchase their own car. Those that can afford to use public transport travel using matatus as well as walking. The residents who cannot afford any form of transport are forced to walk. Salon and Aligula (2012) suggest some policy options that could prevent this transport conundrum from further unravelling: making non-motorised forms of transport (i.e. walking and cycling) safer; improving the attractiveness of public transport by creating services that cater to low income users as well as high income users, which will reduce the number of cars on the road; and increase government oversight of the transportation system.

2.4.7 Conclusion to Case Studies

Regarding the implementation of the BRT, SANTACO was quoted as saying, ‘‘For more than a century to date, the taxi industry successfully moved millions of people without subsidy competing against the state subsidised buses and trains. . . We endured the pains of the imposed deregulation era that led to violence and loss of lives because of the self-centred interests of the apartheid regime, 14 years into democracy we are now confronted with a roundtable systematic plot to nicely get rid of us'' (Woolf et al., 2013).

South Africa, in contrast with South America, has not been able to effectively implement the BRT system as the main form of public transport. Despite millions of Rands invested into various BRT systems throughout South Africa, most public transport users are still opting to make use of the minibus taxi system due to its door-to-door service and its demand responsiveness. It is evident that passengers prefer this service, despite the comfort that the BRTs offer and the, sometimes, dangerous behaviour displayed by minibus taxi operators. This indicates to a disconnect between government driving huge sums of money into an under-performing public transport system and the ordinary South African. An argument can be made for the necessity of the minibus taxi industry in South Africa. Arrive Alive was quoted as saying, "The minibus taxi industry is today the most critical pillar of our public transport sector" (Arrive Alive, 2014).

2.5 TRANSIT PRIORITY MEASURES

Transit priority measures are interventions undertaken 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, 2018).

The currently available transit priority measures that have proven to be effective in the public transport sphere, particularly pertaining to buses, will be considered in the research and will be discussed in the following section.

2.5.1 Curb-side Bus Stops

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).

There are four typical loading area designs which are illustrated in Figure 2-7. They consist of linear loading areas, used for on-street bus stops as they occupy the least amount of space; and non-linear loading areas that include sawtooth, drive-through, and angle designs which allow buses to pull in and out independently of each other (Transportation Research Board, 2013).

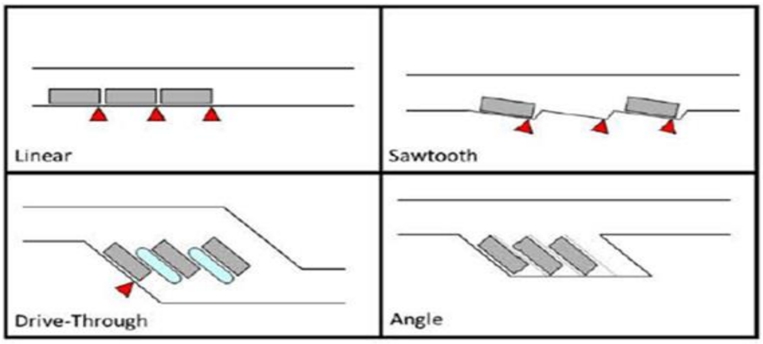


Figure 2-6: Loading area design types (Transportation Research Board, 2013)

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. Bian et al. (2015) proposed a compound Poisson service time estimation model where the interactions among buses arriving and the number of boarding and alighting passengers is investigated.

The process of the service of a bus at a bus stop was described according to the following steps:

1.) The bus enters the lane that contains the curb-side bus stop,
2.) The bus reduces its speed while approaching the bus stop service area and this may cause queueing to occur,
3.) As the bus enters the service area, the front and rear doors open for passengers to board and alight the bus,
4.) Passengers move to their desired positions on the bus whilst the front and rear doors close,
5.) The bus leaves the bus stop area to re-enter traffic where possible delays will occur,
6.) The bus merges with the traffic flow.

With regard 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. Figure 2-7 illustrates that for a given frequency, the queueing delay increases with an increase in bus size; Figure 2-8 shows that the increase in queueing delay is amplified as more berths are provided on the bus stop; and Figure 2-9 illustrates the sizable influence that dwell time has on the queueing delay.

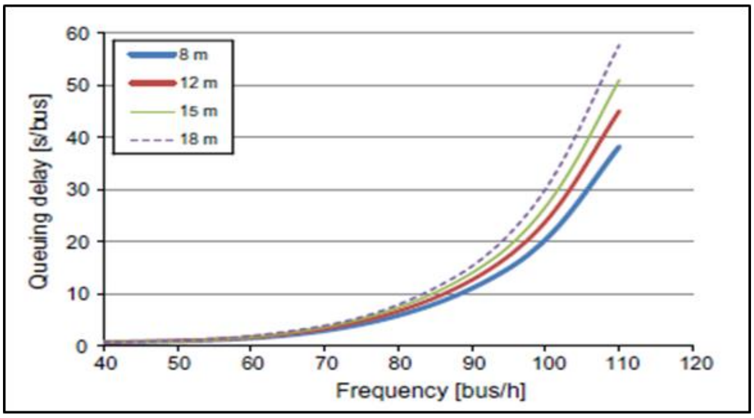


Figure 2-7: Queueing delay for buses 8, 12, 15, and 18 meters, 1 berth, dwell time 20 s

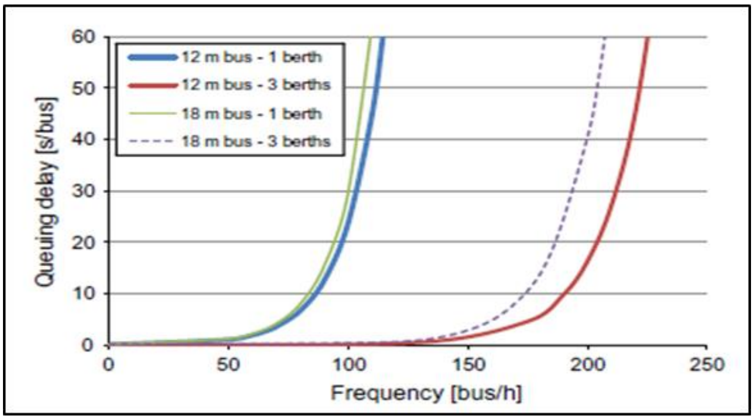


Figure 2-8: Queueing delay for buses 12 and 18 meters, 1 and 3 berths, dwell time 20 s

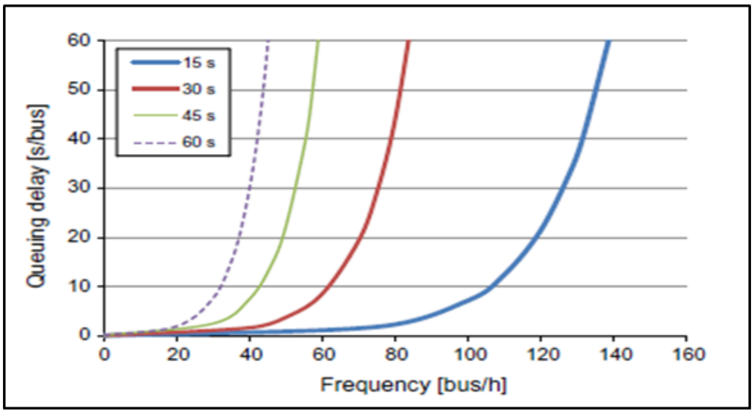


Figure 2-9: Queueing delay for 12-meter buses, 1 berth, dwell time between 15 and 60 s

The service time estimation was used as the basic model for the study and considers the number of passengers boarding and alighting the bus and the dead time (Bian et al., 2015):

$$T = C_d + max\{\sum_{h=1}^{m} a_h , \sum_{q=1}^{n} b_q\} \tag{1}$$

Where:

T : Bus dwell time at bus stop

a_h : Consumed time of each passenger h for boarding

b_q : Consumed time of each passenger q for alighting

m : Number of boarding passengers

n : Number of alighting passengers

C_d : Time for opening and closing doors

There are two types of time delay that can occur at a curb-side bus stop: this first is when, as described in Step 2, a bus can only enter a service area when there is enough space otherwise it must wait for one to open. The second type of delay occurs, as described in Step 5, when the bus attempts to re-enter traffic but has to wait for a large enough gap. The following equations contain the revised service time formulations:

$$T_s = T_d + T_m \tag{2}$$

$$T_d = C_d + max\left\{\sum_{h=1}^{m} a_h , \sum_{q=1}^{n} b_q\right\} + t_{we} + t_{wl}$$

$$= T + t_{we} + t_{wl} \tag{3}$$

$$T_m = t_e + t_l \tag{4}$$

The definitions of a_h, b_q, m, n, and C are the same as in Eq. (1)

T_s : Service time at the bus stop

T_d : Dwell time in and/or out of the bus stop

T_m : Time in which buses move in and out of the bus stop

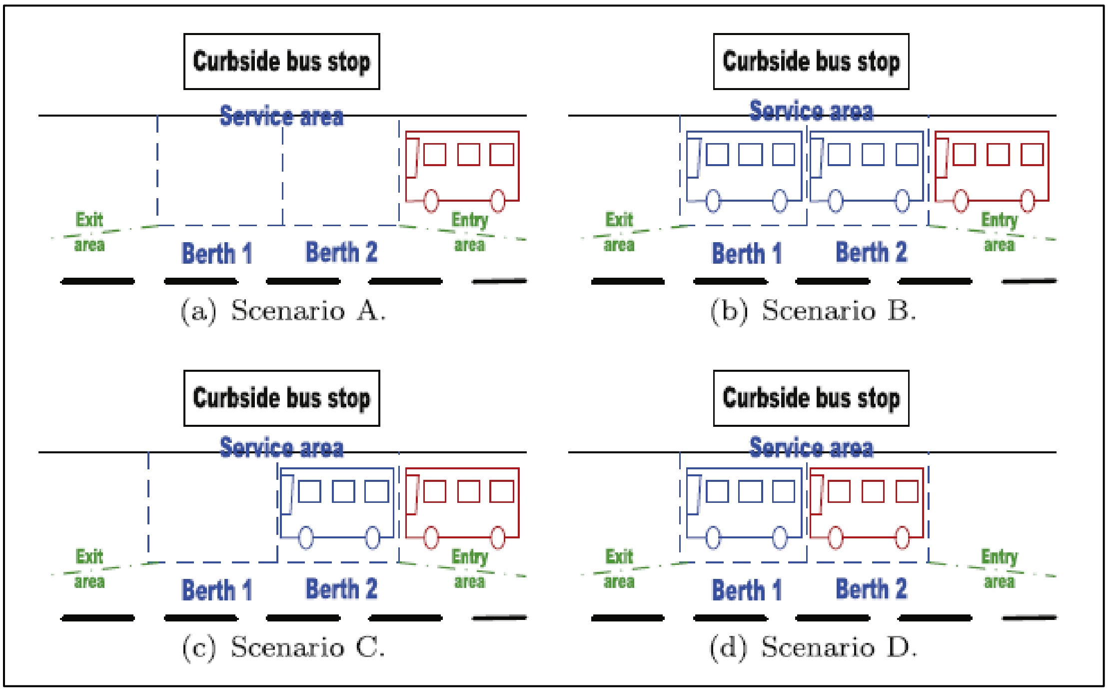
t_{we} : Time in which buses wait to enter the bus stop

t_{wl} : Time in which buses wait to leave the bus stop

t_e : Time in which buses enter the bus stop

t_l : Time in which buses leave the bus stop

To study the phenomenon of queueing Bian (2015) proposed scenarios that a bus can encounter at a curb-side bus stop: in Scenario A the service area is empty, and the bus can leave immediately after the service is completed. For Scenario B, the service area is full, and the bus is required to wait in the entry area. In the third scenario, a single bus waits in the second berth of the service area and the bus entering has to wait for the front bus to leave before it can enter the service area. Finally, for Scenario D, a single bus waits in the first berth of the service area and the bus entering the service area stops in the second berth but must wait for the bus in berth 1 to leave before it can depart. The scenarios are depicted graphically in Figure 2-10.



(a) Scenario A. (b) Scenario B.

(c) Scenario C. (d) Scenario D.

Figure 2-10: Four possible scenarios occurring at a curb-side bus stop with two berths (Bian et al., 2015)

2.5.2 Transit signal priority

Transit signal priority is a general term used to describe a set of operational improvements that use technology to reduce the dwell time for transit vehicles at traffic signals by lengthening the duration of a green signal or shortening a red signal. It is important to note the difference between transit signal priority and signal pre-emption: a signal priority modifies the normal operation of the signal such that transit vehicles can be better accommodated whereas pre-emption interrupts the normal operation of the signal for special events like an approaching train (United States Department of Transportation, 2005).

A study was conducted evaluating the potential benefits of implementing transit signal priority along the Columbia Pike arterial corridor in Arlington, Virginia, with the use of a microscopic traffic simulation model to evaluate what impact a number of alternative strategies would have on in prioritised buses as well as general traffic at morning peak as well as midday traffic periods. Dion et al., (2004) found that providing buses with priority benefit at the expense of the overall traffic, particularly during a high demand traffic period results in reduced travel time, delay, stops, and fuel consumption

2.5.3 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.

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

2.5.4 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 2-11.

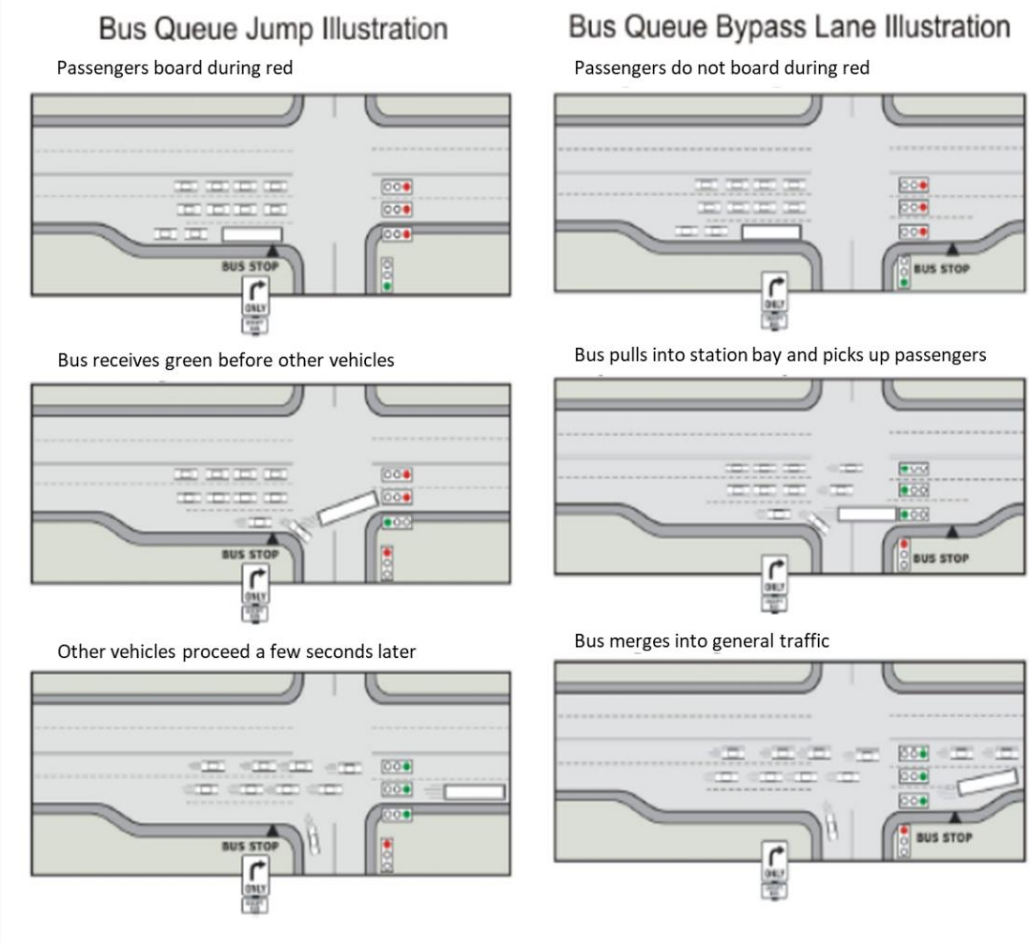


Figure 2-11: Queue jump and queue bypass lane (adapted from Cesme et al. (2014))

Cesme et al. (2014) developed a microscopic simulation model of an isolated intersection using VISSIM to evaluate the potential benefits of transit preferential treatments. The first test compared an intersection with a dedicated right-turn lane with an intersection that has a two-sided queue jump lane as well as a dedicated right-turn lane. The number of vehicles turning right was varied. It was found that as the bus congestion on the queue jump lane decreases, the benefits that they receive also decreases. There was an approximate 10 second reduction in delay as the degree of saturation (v/c) exceeded 0.9 provided the number of right-turning vehicles was less than 100 vehicles per hour. Figure 2-12 illustrates the setup of the two microscopic models that were compared.

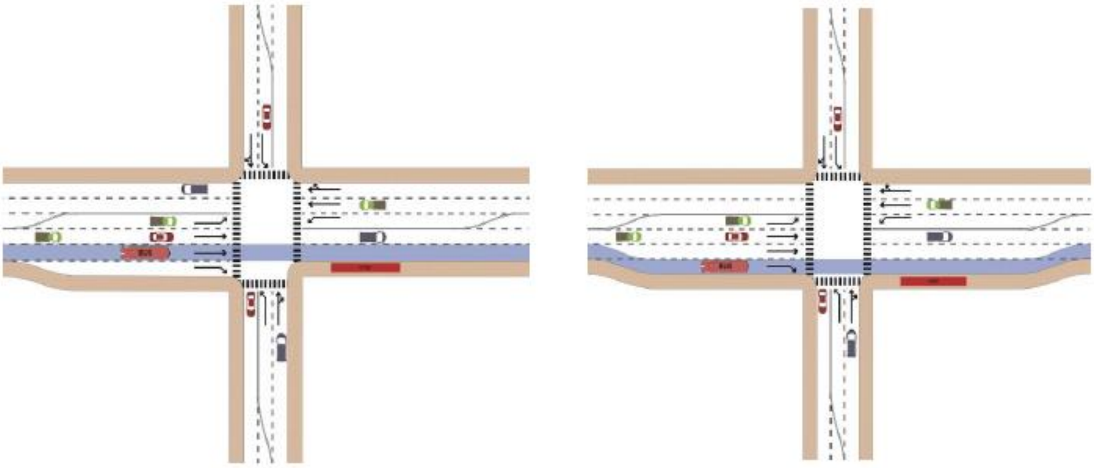


Figure 2-12: (a) No queue jump lane; (b) Two-sided queue jump lane (Cesme et al., 2014)

The second scenario that was modelled included an intersection with no right-turn lane and compared it to an intersection that has a two-sided queue jump lane as well as a dedicated right-turn lane. It was found that the introduction of a queue jump lane results in significant savings when the bus degree of saturation exceeds 0.5. Low bus saturation, however, compounded by high pedestrian demand activity could cause a marginal increase in bus delay. Figure 2-13 illustrates the setup of the two microscopic models that were compared.

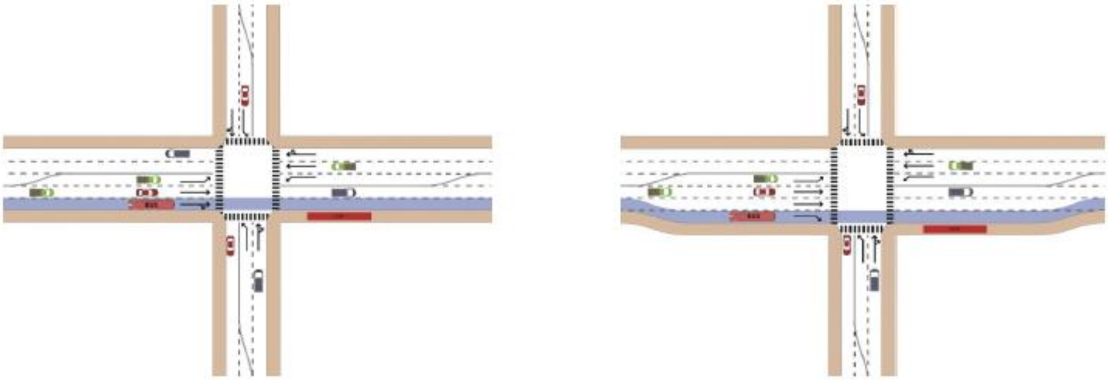


Figure 2-13: (a) No queue jump lane or dedicated right-turn lane; (b) Two-sided queue jump lane (Cesme et al., 2014)

2.5.5 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 2-14 illustrates the setup.

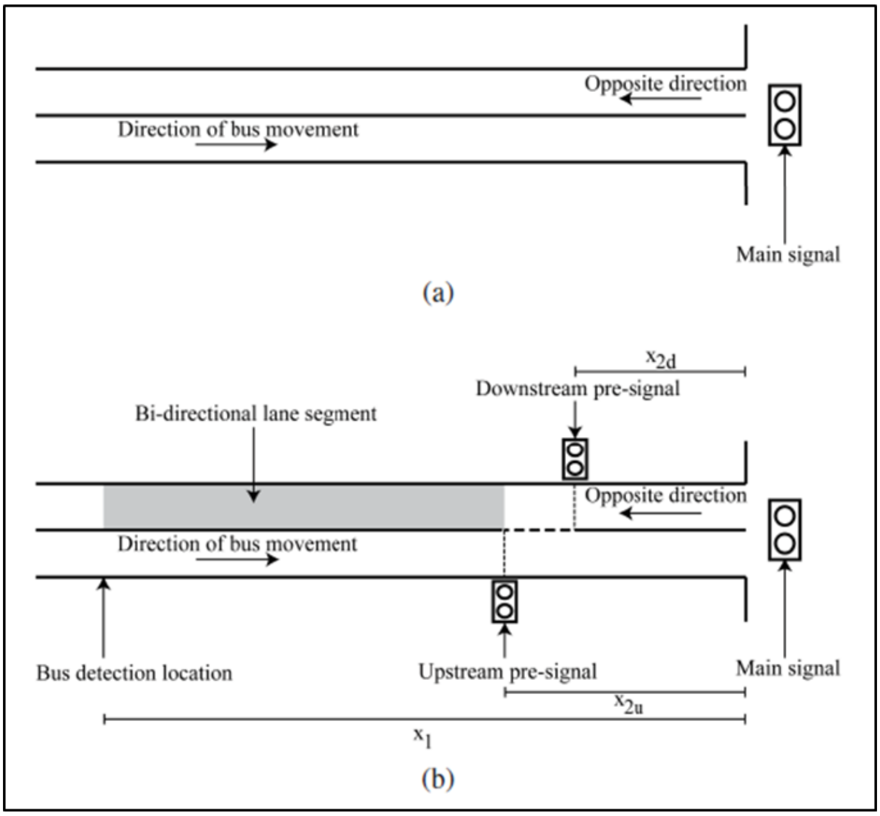


Figure 2-14: (a) Intersection with single lane approaches; (b) Pre-signal strategy (Ilgin Guler et al., 2015)

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 sigle-lane approaches under the following conditions:

- V/C less than 0.85,
- A distance of at least 7 meters between the pre-signal location and the intersection,
- 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%.

2.5.6 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.

Stamos et al. (2012) evaluated the HOV 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. A specific road axis of three streets were totalling 1.6 km in length was located in the CBD area of the city. Although this section serves a lower traffic volume when compared to the adjacent streets, it has a significant function as it is one of three axes that provides a connection from the eastern to the western part of the city. A graphic representation of this area is shown in Figure 2-15.

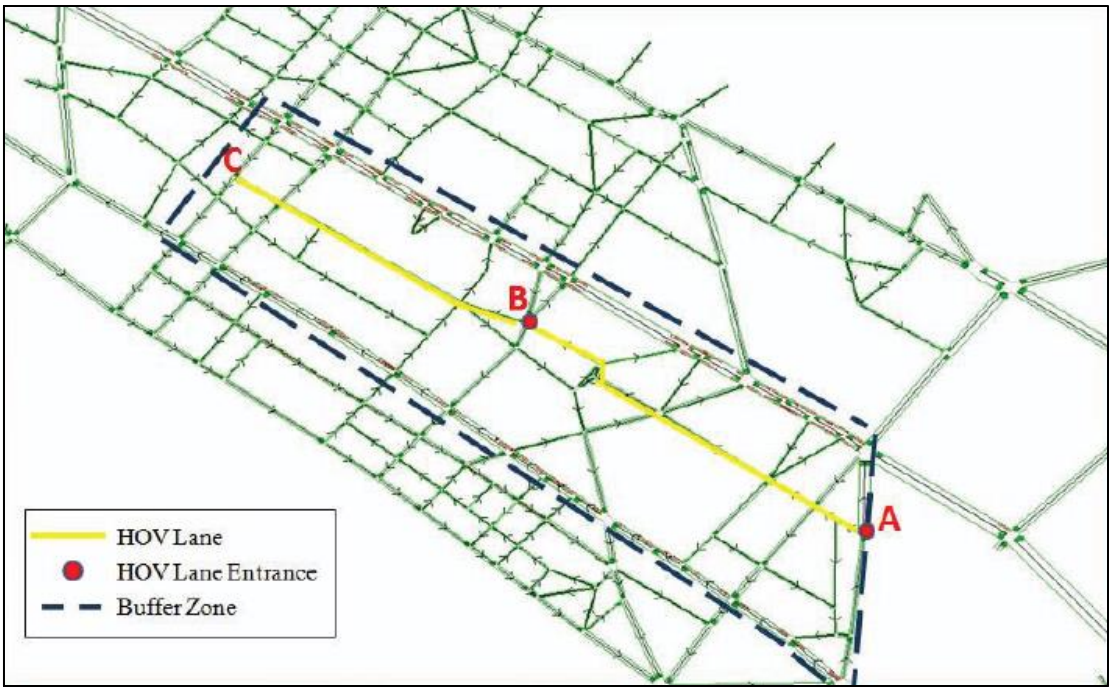


Figure 2-15: Graphic representation of the road axis in the city CBD (Stamos et al., 2012)

With the help of a traffic simulation model the HOV lane addressed the desired outcomes of the experiment: both the traffic and environmental conditions on the road axis of implementation were ameliorated.

The implementation of the HOV lane saw a 6% drop in traffic which was 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%. There was also a significant reduction in pollutant emissions: 42% decrease in CO_2, 67% decrease in NO_X, 50% decrease in HC, and 43% decrease in CO emissions. The fuel consumptions also saw a 41% decline in l/hr.

In the buffer zone – the streets adjacent to the HOV road axis – the traffic increased by 2%, the average delay increased by 7%, and the average speed dropped by 10%. When the positive effects of the HOV lane on the axis itself and the relatively small negative effects on the buffer zone are considered, the HOV scheme meets the goals that were set initially.

2.5.7 Comparative studies of transit priority measures

Much research has been conducted on the effects that transit priority measures have on reducing delays on congested roads. Chitauka and Vanderschuren (2014) investigated the effect that transit priority measures would have on buses. They found that in all the cases, namely bus queue jumps, dedicated bus lanes on the kerbside, and dedicated bus lane in the median lane, when compared to the baseline case, travel speeds increased by up to 131% and travel delay decreased by up to 32%. The net effect that these interventions had on vehicles, however, amounted to a 19% decrease in speed and a 6% increase in delay. What was significant from the study were the results obtained from the kerbside minibus-taxi lane which had a positive net effect for both the public transport and the vehicles (80% and 1% respectively). The net effect on mean travel delay was that is was reduced by 31% for the public transport and only an increase of 2% for the vehicles.

The findings from this study, however, have largely not been extended to include the minibus taxi, and, since the taxi industry is responsible for the transportation of 65% of the South African population (van Zyl, 2009), it is necessary to determine what benefits, if any, such infrastructure would have.

2.6 PUBLIC TRANSPORT NETWORK ANALYSIS AND MODELLING

The decrease in the use of public transport among the urban population can be attributable to factors such as socioeconomic growth, urban sprawl, and the need for personalised mobility. These factors lead to an increase in private vehicle ownership and, as a result, a decrease in the use of public transport as a method of daily commuting (Pucher et al., 2007). The improvement of services such as line capacity, coverage, service frequency, comfort, reliability, and quality of service are necessary to encourage public transport use (Vuchic, 2004). It is therefore necessary to plan and design a service- and cost-efficient transportation network to ensure its improved competitiveness and market share (Kepaptsoglou et al., 2009).

2.6.1 Design of a Public Transport Network

Network design is an important part of the process of public transportation operation planning. This includes designing route layouts and determining associated operational characteristics like frequencies and rolling stock types. Network design elements form part of the overall operational planning process which consists of four steps (Ceder, 2001):

1.) Network route design
2.) Setting timetables
3.) Scheduling vehicles to trips
4.) Assignment of drivers

Public transportation must serve its important social function and at the same time keep the operating costs as low as possible. Objectives should thus encompass both angles when designing the daily operations of a public transportation system. The objectives of a transit route network design are summarised as follows (Fielding, 1987; Van Oudheusden et al., 1987; Black, 1995):

- Maximisation of user benefits
- Minimisation of operator costs
- Total welfare maximisation
- Maximisation of capacity
- Conservation of energy
- Optimisation of individual parameters

The objective viewed by most researchers as the most important is the optimisation of total welfare which includes both benefits to the user and to the system (Kepaptsoglou et al., 2009).

User benefits include travel, minimisation of transfers, operating costs, waiting time and fleet size, and maximisation of coverage and profits.

The characteristics and design attributes that must be considered to realistically represent a transportation network consist of decision variables, the network structure, demand patterns, demand characteristics, operational strategies, and constraints. The decision variables define the layout and operational characteristics, and these include the routes and frequencies of the public transportation network, which can then be used to determine the optimal route spacing, and optimal frequencies per route. Fares, zones, stop locations, and bus types can also be considered as decision variables. According to Kepaptsoglou and Karlaftis (2009), a network structure can either be designed as a simplified radial or rectangular grid road network, however, approaches used since the 1980s were applied to networks that were either realistic, irregular, or not specified at all.

The third parameter, demand patterns, describes the nature of passenger flows to be accommodated by the public transportation network. This therefor dictates its structure: a *many-to-one* demand pattern is characterised by transit trips originating from many areas to a single destination or vice versa typically encountered with a transportation system connecting a CBD to a suburb. A *many-to-many* demand pattern, by contrast, corresponds to flows between multiple origins and destinations which is characteristic of a transportation system in an urban area.

Demand, the fourth parameter, can be characterised either as *"elastic"* or *"inelastic"* where inelastic demand is also known as fixed demand. Elastic demand is a function of either service, space, or time. Service dependent inelastic demand can be affected by transportation services with the total travel demand being kept constant or the total travel demand varies as a result of the transportation service performance. Fares are also directly related to service demand. Headways and route spacing affects the function of space and the function of time is affected by travel time. Operational strategies, developed to improve capacity and system performance of a public transportation network, have mostly been examined at the bus line level. However, the strategies that have been examined include express lines, skip-stops, dead-heading, short turns and route deviations.

The last parameter, the constraints, can be either performance- or resource-based: performance-based constraints include the range of feasible frequencies, maximum and minimum load factors, the route shape, maximum length, and the number of routes. Resource-based constraints are made up of the bus fleet and operational budget.

There is a diversity of approaches in formulating and solving a transit route network design and can be categorised into two main groups: analytical and heuristic approaches. Conventional methods include analytical models and mathematical programming formulations where the analytical models focus on developing relationships between the public transportation network components. Heuristic approaches are an alternative to analytical models and are used to improve the transit route network representation and results while reducing the need for computational power. The two main approaches used within the heuristic approach are route generation and configuration, and route construction and improvement. The methodology and technique selected is influenced by the selected level of detail in the design environment, the quality of the solution that is anticipated, and the available computational power.

Figure 2-16 illustrates the general framework used for the development of a transit route network.

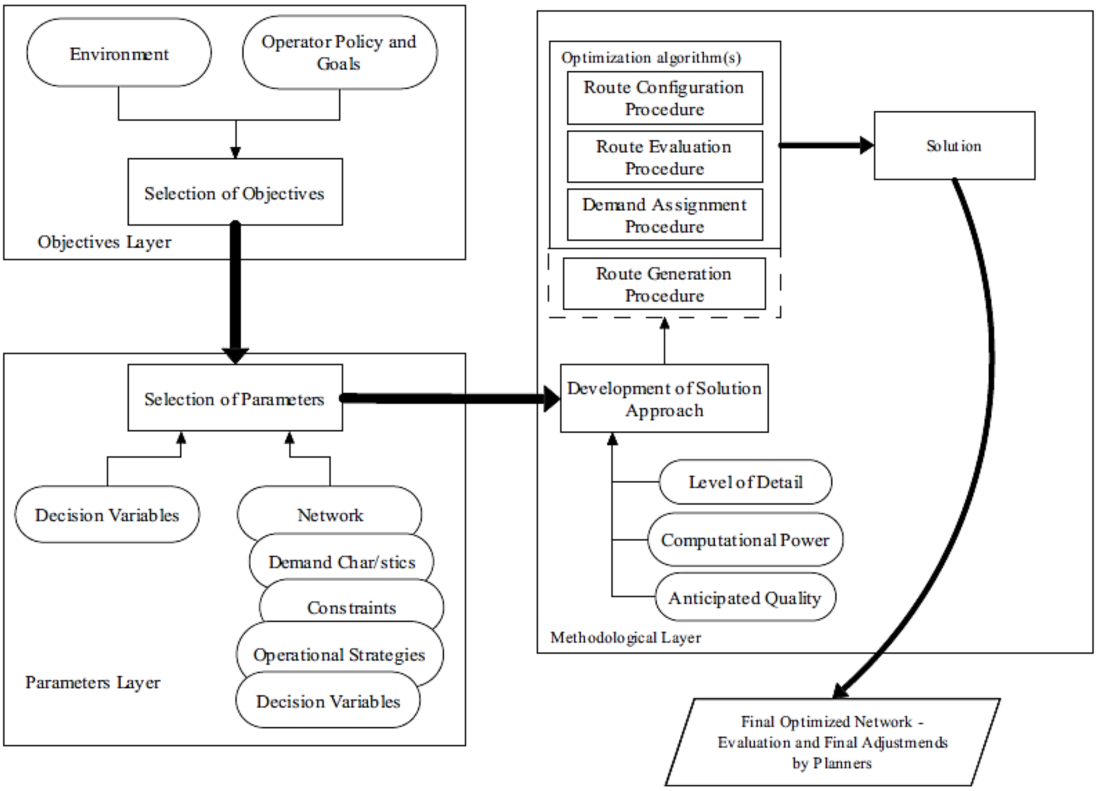


Figure 2-16: General framework for a transit route network design (Kepaptsoglou et al., 2009)

2.6.2 Development of a Public Transport Cost Model

Engineering cost models are used to compute the total cost of technical project element or service over a given time, typically a year. The cost components in the model consist of terms proportional to the consumed resource made up of measurable or calculable resource input quantities and asset commitments required to provide a certain service **(Bruun, 2007).**

The costs of public transport services include two main components: capital costs and operating costs (del Mistro et al., 2000). Capital costs are annualised by looking at the analysis period, the life of the investment, the interest rate, and the residual value at the end of the analysis period. Capital costs, when used to estimate the cost of public transport serviced, include the following:

- Vehicle cost including refurbishments or overhauls during its service life or the analysis period.
- Cost of the route.
- Cost of the terminals.
- The cost of stations and shops.
- The cost of depots.

Operating costs include:

- The cost of fuel.
- Vehicle operating costs which include operating staff costs, management costs, office rentals, insurance, overheads, licence costs, marketing, and vehicle maintenance.
- The annual cost to operate and maintain the roadway as well as the annual staff costs.
- The annual cost to operate the depot.

Bruun (2007) states that the resource variables, Vehicle-Hours, Vehicle-Distance, and peak Fleet Size, drive the estimated operating cost of different scenarios when applied to public transportation and the unit coefficients, c_{VH}, c_{VD}, and c_{FS}, represent the cost that is attributed to each respectively. The final term denotes the asset commitment which is represented by the annualised ownership cost of a vehicle that costs P in year 0. The total short-term operating cost is estimated with the following model:

$$\boldsymbol{AC_T = c_{VH} \cdot (Vehicle\ Hours) + c_{VD} \cdot (Vehicle\ Distance) + c_{FS} \cdot (Fleet\ Size) + P(CRF)} \quad (5)$$

where AC_T represents the annualised total cost.

Brunn (2007) further provides a systematic method for assigning short-term expenditures to the various resource variables. Expendables like tires are consumed in direct proportion to the vehicle-distance travelled whereas operator pay is directly proportional to the number of vehicle-hours operated. Fuel and vehicle maintenance, however, are functions of both vehicle-hours and vehicle-distance and therefor the fractions X and Y and well as their complements are introduced.

The annualised operating cost is the same as the annualised total cost save for the omission of the vehicle ownership cost:

$$AC_0 = c_{VH} \cdot (Vehicle\ Hours) + c_{VD} \cdot (Vehicle\ Distance) + c_{FS} \cdot (Fleet\ Size) \qquad (6)$$

The author gives two reasons for the omission: the first being that the operator is not responsible for this cost but receives a grant for this purchase instead. The second reason is that the vehicle is no longer required for the route and is put to use elsewhere in the system or put in storage when it has become worn out. The cost is therefore treated as a sunk cost and not a variable cost.

Table 2-1 shows an example of a typical cost allocation matrix.

Table 2-1: Typical cost allocation matrix

	Vehicle-Hours	Vehicle-Distance	Fleet Size
Vehicle Operators	C_o		
Fuel	$(1-X)C_f$	XC_f	
Tyres and other expendables		C_t	
Vehicle Maintenance	$(1-Y)C_m$	YC_m	
Facility Maintenance			C_{fm}
Administration			C_a
Supervision and Control Centre			C_s
Other			
TOTAL	C_{VH}	C_{VD}	C_{FS}
Unit coefficients:	$C_{VH} = C_o/VH$	$C_{VD} = C_{VD}/VD$	$C_{FS} = C_{FS}/FS$

Where:

C_o : Vehicle operating cost

C_f : Fuel cost

C_t : Cost of tyres and other expendables

C_m : Cost of vehicle maintenance

C_{fm} : Cost of facility maintenance

C_a : Administrative costs

C_s : Supervision and control centre cost

2.6.3 User Cost in Transportation Modelling

Proboste et al. (2016) developed a model for a generic *ij* origin-destination pair of travellers travelling along the same route.

$$\sum_{i,j\epsilon M} Q_{ij}(\gamma_a \overline{T_a^{ij}} + \gamma_w \overline{T_w^{ij}} + \gamma_w \overline{T_{tw}^{ij}} + \gamma_v \overline{T_v^{ij}} + \tau_{ij}\Delta) \qquad (6)$$

The model consists of five components, the first of which is the traveller's access/egress time, which is the average distance that a user of the micro-zone has to cover to get to or from their closest stop, divided by their access or egress speed.

$$\overline{T_a^{ij}} = \frac{\overline{L_i}}{V_a} + \frac{\overline{L_j}}{V_a} \qquad (7)$$

Where:

$\overline{L_i}$: Distance to the closest bus stop (km)

$\overline{L_j}$: Distance from the bus stop (km)

V_a : Access/egress speed (m/s)

The second term is the initial waiting time which is the time users have to wait to board their first bus of their trip assuming that the lines operate without a schedule. The sum of the frequencies of the common lines set is considered to calculate the initial waiting time and a constant k value of 0.5 is used as the bus arrival is assumed to be evenly spaced whereas passengers are assumed to arrive randomly.

$$\overline{T_w^{ij}} = \frac{k}{\sum_{l\epsilon L_1^{ij}} f_l} \tag{8}$$

Where:

k : 0.5 (Buses arriving at evenly spaced intervals and passengers arriving randomly)

f_l : Line frequency

The third element, waiting times for transfers, is modelled the same way as initial waiting time but the line frequencies from the respective trip stage is used. In-vehicle travel time, the fourth element, is calculated using the cycle time equation:

$$\overline{\boldsymbol{T_v^{ij}}} = \left[\frac{\boldsymbol{D_l^p}}{\boldsymbol{V_p}} + \frac{\boldsymbol{D_l^c}}{\boldsymbol{V_c}}\right] + \left[\left(\boldsymbol{t_{ba}^{pl}} + \boldsymbol{t_{ba}^{cl}}\right) + \left(\boldsymbol{t_s^p n_l^p} + \boldsymbol{t_s^c n_l^c}\right)\right] \tag{9}$$

Where:

V : Speed of buses in motion on the trunk (t) or feeder (f)

t_{ba}^l : Time required for passengers to board (b) and alight (a) the bus on the trunk or feeder route

t_s : Extra time required to accelerate, decelerate, and open and close doors on the trunk or feeder route

n_l : Number of stops on the trunk or feeder route

Finally, the last component of user cost, transfer penalty, which represents all costs that users perceive when transferring including walking and trip interruptions. This cost component is influenced by the context of the transfer like the weather or the safety of the neighbourhood.

2.7 CONCLUSION TO LITERATURE REVIEW

The genesis of the minibus taxi industry in South Africa arose due to a significant gap in the public transport market being realised: the black community living on the outskirts of large cities were able to make use of a dynamic, demand-responsive form of transport at affordable rates.

In recent, years attempts have been made to reform the paratransit industry primarily through integrating it with the BRT system. The cities of Johannesburg and Cape Town both followed similar transformation and reform models: minibus taxis owners and operators had to agree to relinquish their travel routes and in return would be offered participation in the new BRT process. In Johannesburg, the Reya Vaya system should be able to transport a total of 102 000 commuters each day but instead the service is only being used by an average of 35 000 people. The implementation of the BRT in South Africa has not been as effective as it has been in South American countries. The minibus taxi is still the preferred mode of transportation for the majority of South Africans that make use of public transportation. Despite having proven to be effective in its dynamic service and pedestrian reach, the minibus taxi industry faces great challenges which includes road crashes, mainly due to defective brakes and pressure being put on drivers to perform, taxi violence due to disputes between different taxi associations, a lack of formal training and no employment protection. The main challenges, however, stem from their need to survive financially and therefor providing minibus taxi operators with road infrastructure that would give them an advantage in traffic would go great lengths in reducing their difficulties.

Four forms of transit priority infrastructure were identified, namely, the queue-jumping lane, the queue-bypass lane, the single lane pre-signal strategy, and the dedicated public transport lane. It is the endeavour of this document to design a corridor that includes each form of infrastructure and compare it to the curb-side taxi stop base case. These forms of infrastructure have proven to effectively shorten the travel time for buses or BRT vehicles but little to no research has been conducted to determine the effectiveness of these transit measures as they apply to minibus taxis in South Africa. This report will address this issue.

3 MODEL DESIGN

3.1 INTRODUCTION

This chapter discusses the methodology followed to develop the five transit priority measure models. The methodology can be summarised in the following sections:

- Analytical mathematical modelling
- Steps in developing an analytical mathematical model
- Model scope
- Model input variables
- Model output variables
- Discussion

3.2 ANALYTICAL MATHEMATICAL MODELLING

Mathematical modelling is used to translate certain beliefs people have about how the world functions into the language of mathematics which has many advantages, namely (Marion, 2008):

1.) Mathematics is a precise language which helps the modeller formulate ideas and identify their underlying assumptions,
2.) Mathematics is a concise language and manipulation of the model can be performed according to well-defined rules, and
3.) Computers can be used to perform numerical calculations.

The objectives that can be achieved in mathematical modelling include:

1.) Developing a scientific understanding of the system,
2.) Testing the effect of changes in the system, and
3.) Aid in decision making which includes strategic decisions made by planners.

Excel was the main software used in which to carry out the modelling process, also known as “spreadsheet simulation”. According to Seila (2004) the capabilities that must be available for a spreadsheet simulation to be utilised must include:

1.) A way to represent mathematical and logical relationships and algorithms describing how to complete a series of computations. The relationships can be represented either in the form of computations or by the assignment of values.
2.) A means to generate distributed pseudorandom numbers uniformly to be used to sample observations from various distributions.
3.) A way to repeat a series of computations such that replications can be implemented.

3.3 STEPS IN DEVELOPING AN ANALYTICAL MATHEMATICAL MODEL

The development of the model followed a basic five step process which consisted of the formulation of the problem statement, defining the objectives, building the model using Excel, calibrating the model using field data, and reporting on the results. Figure 3-1 illustrates the process followed.

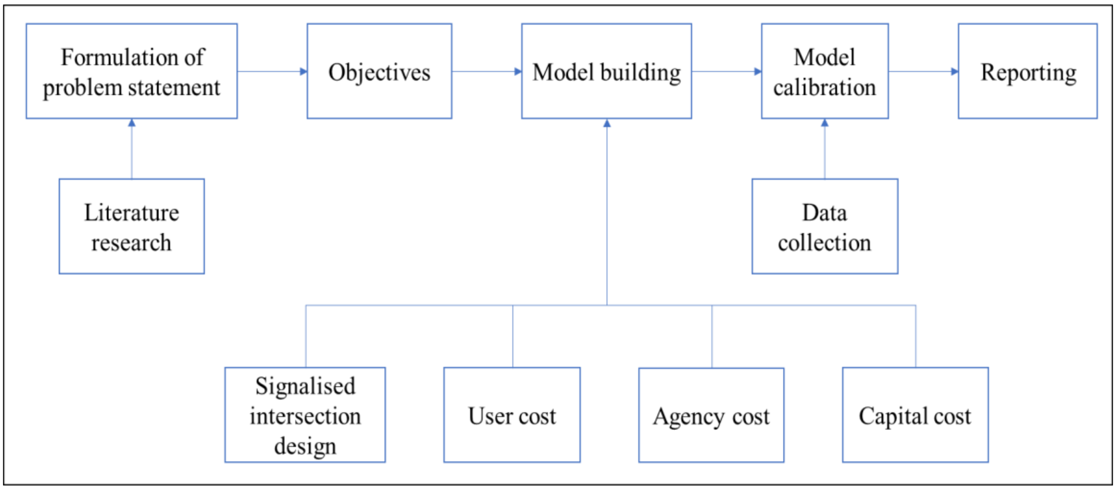


Figure 3-1: Simplified simulation problem analysis and solution process

3.4 MODEL OBJECTIVES

Five forms of infrastructure were chosen based on Chapter 2, namely, a curb-side taxi stop, a queue-jumping lane, a queue-bypass 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, the passengers, other road users, and society at large. 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. It would then be possible to draw a queueing diagram of the phases pertaining to each infrastructure form.
2.) The user cost which entailed the time passengers in the minibus taxis as well as private vehicle owners spent on the road. This time could then be converted into a monetary value.
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 five forms of transit infrastructure.

3.5 MODEL SCOPE

The model consists of five main modules, namely, the situation sheet, the information sheet, the calculating sheet, the summary sheet, and the sensitivity sheet. Each module is discussed in the subsequent sections.

3.5.1 Situation Sheet

The situation sheet contains the description of the transit priority infrastructure that is to be provided in the form of a sketch. The model will consider traffic along a single route through the intersection from left to right. Cross-street traffic was not considered as only the benefits pertaining to the left to right movement where the transit infrastructure is to be implemented was of significance in this research. Minibus taxis and private vehicles were also assumed to always drive straight through the intersection as left and right turns would affect the outcome of the results and are also not of significance when the benefits of the transit infrastructure is being investigated.

For the first form of infrastructure, curb-side taxi stops, the most advantageous location must be established. The location of bus stops in urban networks are classified into three groups: *nearside* stops which are stops before an intersection, *far-side* stops which are found after the intersection, and *midblock* stops which are stops that are isolated from intersections (Tirachini, 2014). Several factors need to be considered when determining the most optimal bus-stop location like programming of signalised intersections, the size of the bus stop, the geometry of the access to the curb, the number of vehicles turning left or right at the intersection, traffic safety, and pedestrian movement. When the bus stops are analysed in isolation from those up- and downstream, far-side bus stops were found to be more favourable than midblock or nearside stops.

The intersection consists of a North-South and an East-West single 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 curb-side stop. This form of infrastructure will be considered as the base case against which to compare all the subsequent forms of priority infrastructure. Figure 3-2 illustrates the schematic model upon which calculations will be based. All taxi stops in the subsequent figures are indicated with a red triangle.

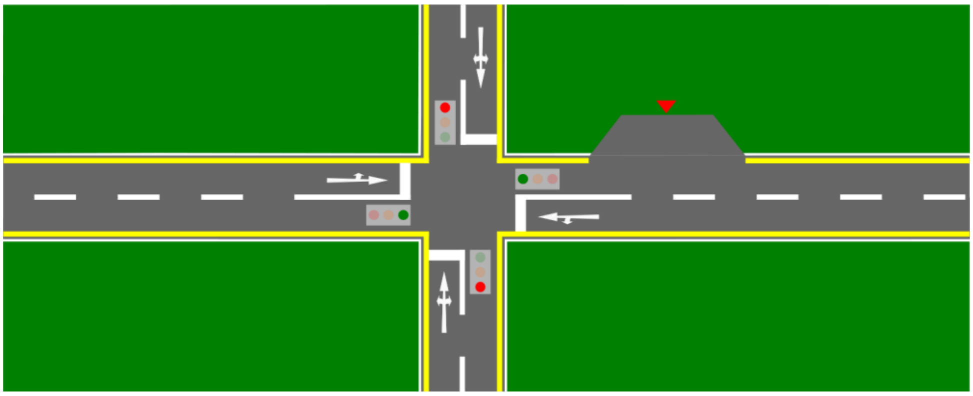
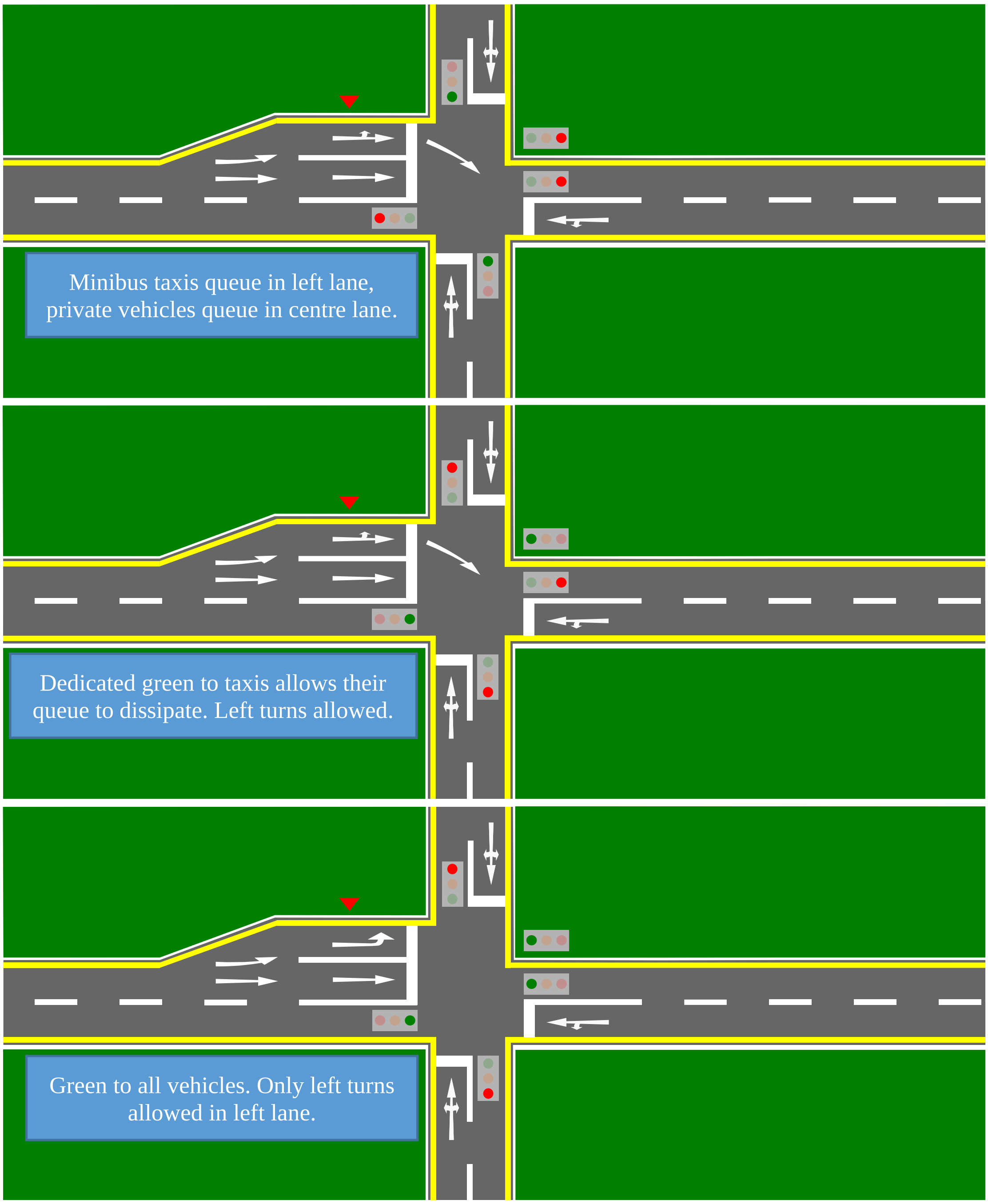


Figure 3-2: Schematic representation of the curb-side taxi stop

The second transit priority infrastructure, the queue-jumping lane, allows the minibus taxis to skip the entire queue at the intersection by providing them with a dedicated section of road. During the red period for the travellers on the East-West road, the minibus taxis will form a queue in this lane after which they will receive a dedicated green period allowing the taxi queue to dissipate. After the dedicated green cycle, the traffic signal will be green for all vehicles travelling in the East-West road, also called the *all-green* phase. The one-sided lane previously used as a priority lane will, however, only be used as a left-turning lane during the all-green phase.

During the red cycle phase, taxis can drop off and pick up travellers in the dedicated lane but will not be able to make stops during the priority green phase or the all-green phase. The operation of the infrastructure in its three stages is illustrated in Figure 3-3.



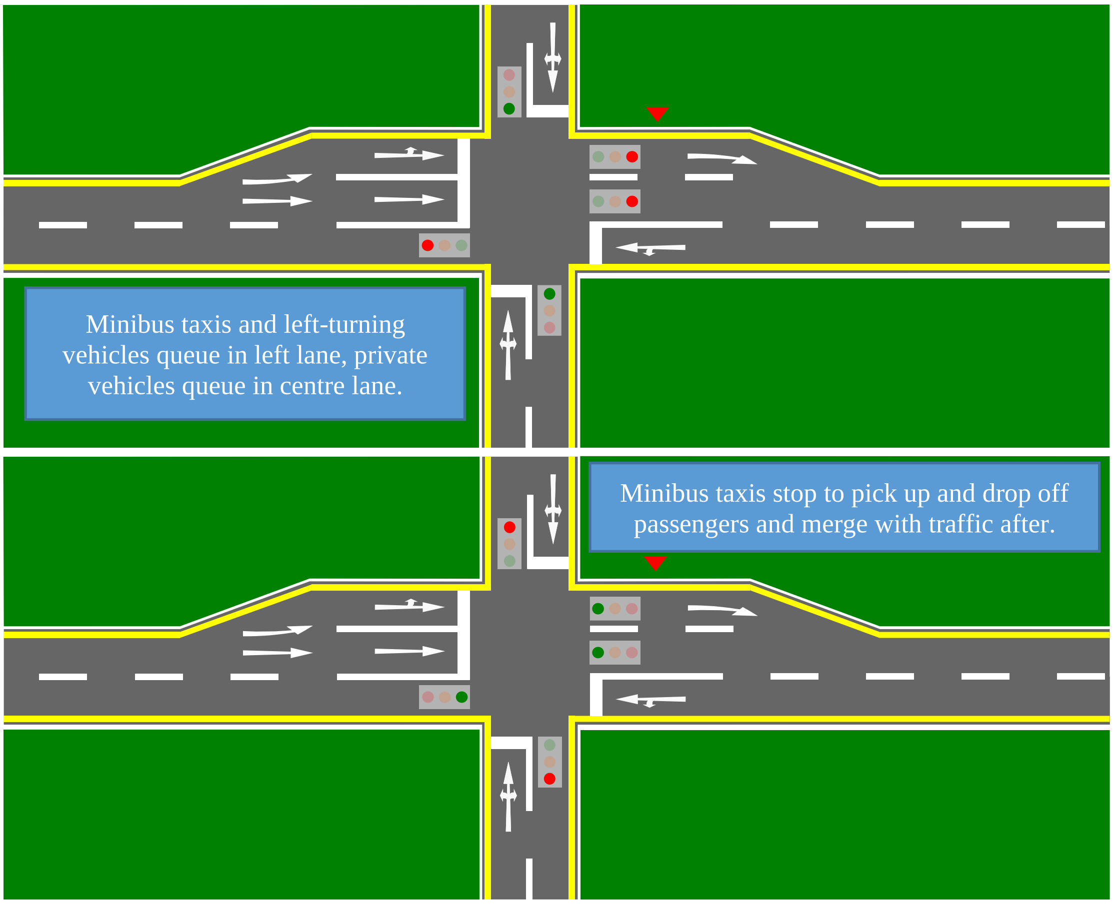
Minibus taxis queue in left lane, private vehicles queue in centre lane.

Dedicated green to taxis allows their queue to dissipate. Left turns allowed.

Green to all vehicles. Only left turns allowed in left lane.

Figure 3-3: Schematic representation of the queue-jumping lane

The potential shortcoming of the queue-jumping lane, that is, the inability of taxi operators to pick up or drop off passengers during the dedicated green and all-green phases, is addressed by the queue-bypass lane. In this case there is no dedicated green phase for the minibus taxis but rather a dedicated road space for minibus taxis on both sides of the intersection. The near-side of the infrastructure will, however, also be used for left-turning vehicles. The taxis will drive along this road, through the intersection and stop on the far-side to pick up and drop off passengers. This benefits taxis in that making a stop at a curb-side stop takes up more time. Taxis that do not need to make a stop will continue driving in the centre lane and those that do need to stop for passengers will do so and then merge with the mixed traffic. The far-side of the road space will be designed to be long enough such that one minibus taxi can merge between every private vehicle. It can be assumed that the number of taxis driving through the intersection would be sufficiently small that no significant bottleneck will form on the far side of the intersection. The two stages of the operations are illustrated in Figure 3-4.



Minibus taxis and left-turning vehicles queue in left lane, private vehicles queue in centre lane.

Minibus taxis stop to pick up and drop off passengers and merge with traffic after.

Figure 3-4: Schematic representation of the queue-bypass lane

The fourth priority infrastructure provides taxis with a time advantage without incurring significant construction costs. During the North-South green cycle, the vehicles on the East-West corridor start to form a queue. At the end of this cycle minibus taxis will be given a priority green cycle where they can use the right lane to cross the intersection thereafter returning to the left lane. After the taxis have cleared the priority lane, the all-green phase will start, and the intersection will continue to function as normal.

The length of the priority section of road is designed to account for the number of private vehicles that will queue over the duration of the East-West green cycle. Only taxis adjacent to the priority section of road will be permitted to use it to gain a time advantage. The three phases of the operations are illustrated in Figure 3-5. It is noted, however, that boarding or alighting of a minibus taxi in the middle of the road is dangerous, and that a raised curb in the centre of the road would have to be constructed to account for this issue.

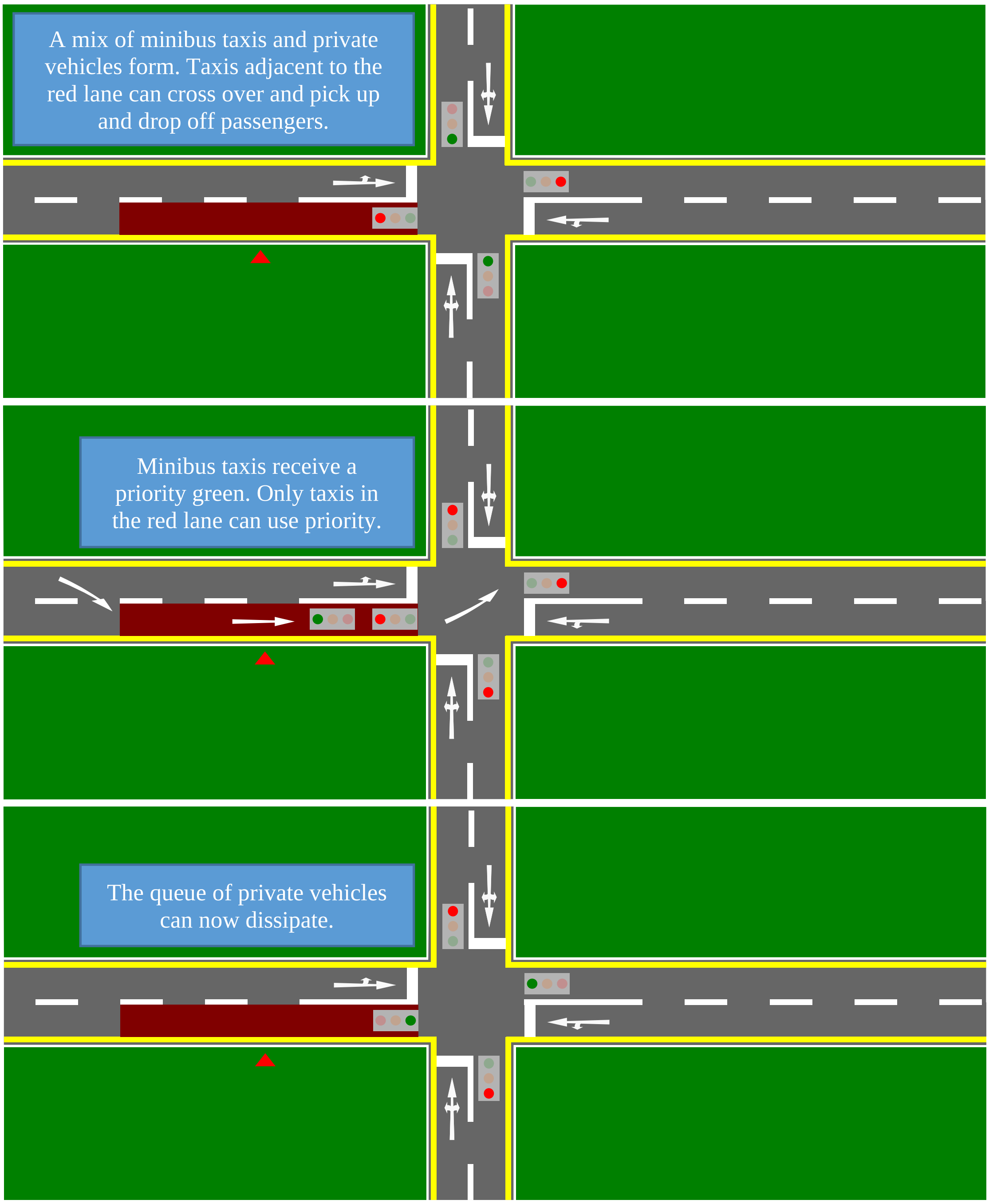


Figure 3-5: Schematic representation of the single lane pre-signal strategy

The final priority infrastructure, the dedicated taxi lane, is expected to provide the public transport with the greatest amount of time savings whilst minimising the delay experienced by regular traffic. A curb-side taxi stop is included as it is assumed that this infrastructure form would be constructed along a busy corridor. The construction costs were calculated, as with all the other priority strategies, and evaluated against the benefits of travel time savings. The representation of the dedicated taxi lane is illustrated in Figure 3-6.

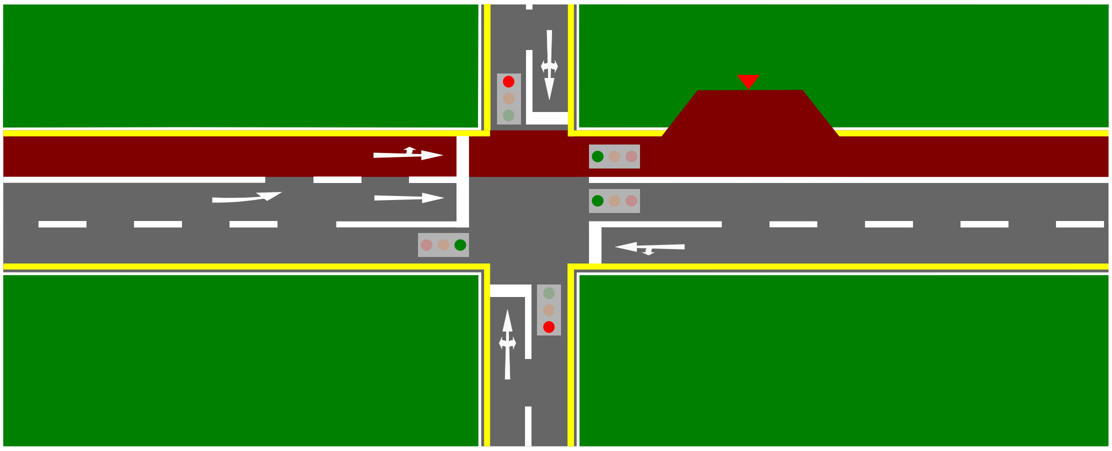


Figure 3-6: Schematic representation of the dedicated taxi lane

3.5.2 Information Sheet

The information sheet contains information pertaining to the travelling speeds, acceleration rates, vehicle capacity, capital costs, operating costs, and energy and fuel consumption. The data and further explanations pertaining to the inputs of the model are explained in Chapter 3.4. Calculations relating to minibus-taxis are based on the most commonly used form of transport, the Toyota Quantum 2.5 D-4D Sesfikile 16-seater bus as shown in Figure 3-7.

Figure 3-7: Toyota Quantum (AutoMart, 2019)

3.5.3 Calculation Sheet

The calculating sheet is where the cost is calculated for the different infrastructure forms. The total cost is calculated as the sum of the user cost, operating cost, and the capital cost of the infrastructure.

3.5.4 Summary Sheet

The summary sheet fits all the relevant inputs and outputs of the Information and Calculation Sheets onto one page for easy comparison between the forms of infrastructure. As final outputs, the model provides:

- One-way travel time
- User cost per hour
- Operator cost per hour
- Cost per space offered
- Fuel cost per one-way trip
- Environmental cost per one-way trip
- Total cost per hour of travel

3.5.5 Sensitivity Sheet

The sensitivity sheet was used to determine the effects of changes in values of ten input parameters on the main outputs of the model. The ten input parameters that were varied include:

- Length of corridor

- Vehicle capacity of private vehicles
- Vehicle capacity of minibus taxis
- Passenger handling time for minibus taxis
- Percentage of minibus taxis that stop to pick up or drop off passengers
- Vehicle-hours minibus taxi operators spend driving in a month
- Vehicle-distance minibus taxi operators travel in a month

3.6 MODEL INPUT VARIABLES

The modelling process requires defining the variables used. The variables are broadly divided into four sections, namely, signalised intersection design, user cost, operator cost, and capital cost. This section 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.

3.6.1 Signalised Intersection Design

The design of the intersection forms the base of the model development: the signalised intersection determined the waiting time at the intersection as well as the queue lengths that formed as a result. These values are then used to determine the subsequent user costs and operating costs.

Table 3-1 provides the input variables used in the signalised intersection design. Each variable is briefly explained.

Table 3-1: Input variables used in the signalised intersection design

Variable	Description
Average delay per vehicle (minibus taxis and private vehicles)	• The average delay per vehicle is given by the following equation: $d_{avg} = \frac{r^2}{2C(1-{}^{v}/_{s})}$ (10) Where: r: Effective red time for a traffic movement in seconds C: Cycle length in seconds v: Arrival rate in vehicles/second s: Departure rate in vehicles/second • This value is used as an input value to determine the red cycle time for each case. • It is kept constant for all the forms of priority infrastructure as well as the base scenario where mixed traffic operates. It is used a control variable rather than an output variable. • An average value of 12 seconds per vehicle, corresponding to a level of service (LOS) B is used. • In the infrastructure forms where minibus taxis receive a priority signal, the average delay is calculated separately for this mode.
Cycle length in seconds	• The time, in seconds, for one complete sequence, for all approaches, of signal indications. This includes greens, yellows, and reds. • The cycle length of 60 seconds is used in the intersection design.
Arrival rate in vehicles/second	• The arrival rate of minibus taxis and private vehicles differ depending on the time of day. • The arrival rate is based on traffic counts that were carried out on a road corridor where different transportation modes operate.
Departure rate in vehicles/second	• Minibus taxis and private vehicles are assumed to have the same departure rate. • The departure rate is assumed to be equal to the saturation flow rate. • A departure rate of 3600 vehicles/hour is used, or 1 vehicle/second.

It is worth mentioning that the delay was kept as a constant in the modelling process rather than generate it as an output. The reason for this is to determine the optimal red time for all vehicles. The endeavour was to provide minibus taxis with some form of priority without causing unnecessary extra delay for private vehicle users.

3.6.2 User Cost

The second section of the model calculations, determining the user cost, depends on the relevant vehicle characteristics for both private vehicles as well as minibus taxis. Some of the characteristics include acceleration rate, vehicle capacity, and vehicle length. The values of the variables that are to be kept constant for the entire analysis were determined from observations performed on traffic footage.

It is also necessary to know the travel speeds of vehicles at various locations in and around a city to determine of the priority infrastructure would be effectively implemented and where. The speeds were obtained from the public transport cost model that del Mistro and Aucamp (2000) developed. Table 3-2 provides a summary of the different speeds as they relate to the possible locations where the infrastructure can be implemented. Table 3-3 provides the salient input variables used in calculating the user cost with each variable being briefly explained.

Table 3-2: Travel speeds at various locations in a city

Location	Speed ($\boldsymbol{Vf}$)
CBD/Commercial in peak	25 km/h
Arterial in peak	50 km/h
Residential in peak	60 km/h
CBD/Commercial off-peak	25 km/h
Arterial off-peak	50 km/h
Residential off-peak	60 km/h

Table 3-3: Input variables used in calculating user cost

Variable	Description
Acceleration and deceleration rate, a	• The acceleration rate and deceleration rate are assumed to be the same for private vehicles and minibus taxis. • The acceleration rate is also assumed to be equal to the deceleration rate. • With the average acceleration rate of most ordinary vehicles being between 3 and 4 m/s^2, a value of 3.5 m/s^2 was used.
Vehicle capacity	• The maximum capacity of a private vehicle is assumed as 5 passengers whilst that of the minibus is taken as 18 passengers. • The values of both the private vehicle and the minibus taxi are varied for the purpose of the sensitivity analysis. • For the base scenario, a ratio of 18 minibus taxi passengers to 1.5 private vehicle passengers is used.
Passenger handling time	• The passenger handling time includes the time a passenger takes to board and alight a minibus taxi. • This variable was not considered with the case of non-public transport forms. • This variable will be varied for the purpose of the sensitivity analysis. • The base value of 8 seconds per passenger is used for the initial modelling.
Time for opening and closing doors, c	• Time taken to open and close doors of the minibus taxi was assumed to be the same as that of a BRT which is 3 seconds.
Vehicle length	• The length of the minibus taxi is based on the length of the Toyota Quantum which is 5.38 m.
Speed on entering the curb-side stop	• This speed forms part of the calculations determining the total service time of a minibus-taxi on the curb-side stop form of service infrastructure. • A speed of 3 m/s was used for the speed at which minibus taxis enter and exit the curb-side stop.

To determine the user cost in terms of a monetary value it is necessary to have a value of time to attach to each of the three main income groups: low, medium, and high. Since the year 2010 several value of travel time savings (VTTS) have been made in South Africa. Different survey types and choice models were conducted to estimate these values (Hayes, 2018). Figure 3-8 graphically depicts the VTTS by market segment for the studies that have been carried out.

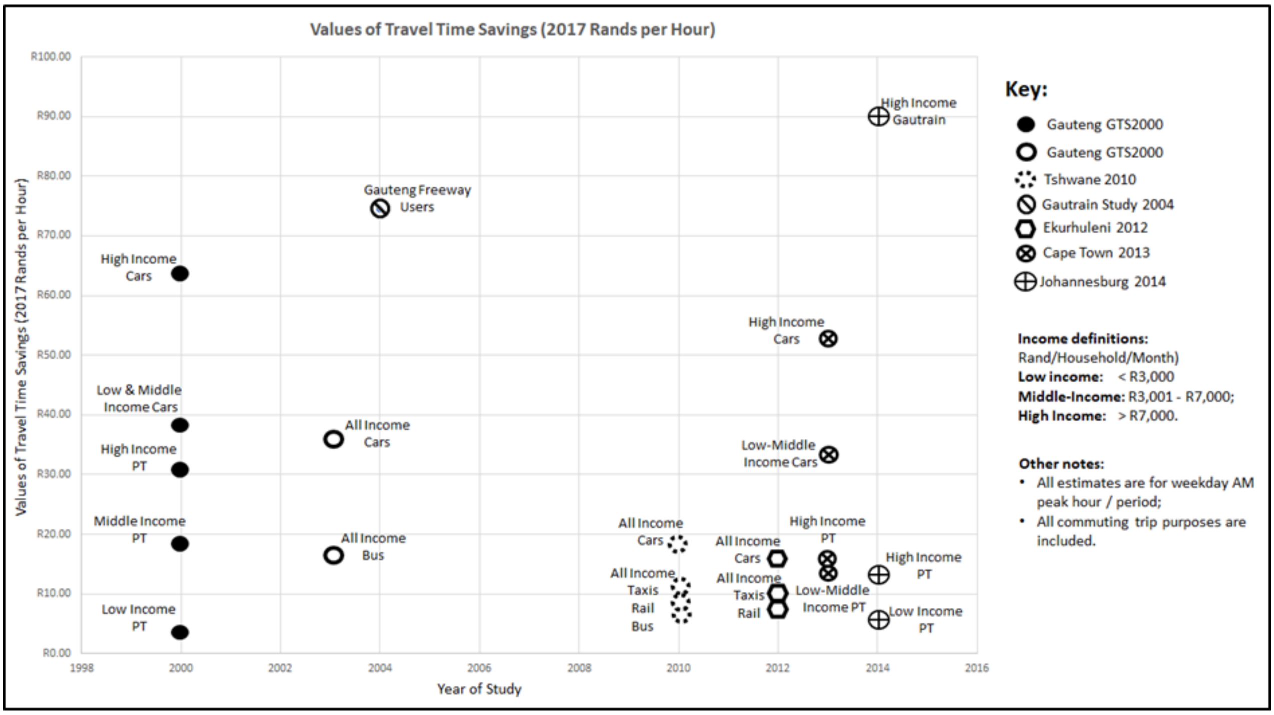


Figure 3-8: South African VTTS for several studies between 2000 and 2014 (Hayes, 2018)

Table 3-4 and Table 3-5 summarise the income groups and their corresponding values of time along with the percentage of each income group that makes use of cars and minibus taxis respectively (Department of Transport, 2013). These values as well as their proportions are used to calculate the value of time as part of the model outputs.

Table 3-4: Private vehicle user income group, value of time, and proportion

Income group	Value of time	Proportion (%)
Low income	R4.00	7.4
Middle income	R18.00	18.5
High income	R31.00	74.0

Table 3-5: Minibus taxi user income group, value of time, and proportion

Income group	Value of time	Proportion (%)
Low income	R4.00	28.1
Middle income	R18.00	45.9
High income	R31.00	26.0

3.6.3 Operator Cost

The operator cost consists of all the costs incurred whilst operating a vehicle. The operating cost of a minibus taxi far exceeds that of a private vehicle as the salary of the operator is included in this cost amongst others. The vehicle operator salary, as well as the subsequent variables in the operating cost pertaining to the minibus taxis, were attained from the Taxi Recapitalisation Viability Model (Department of Transport, 2008). The values were adjusted for inflation using a rate of 4.5%.

Table 3-6 summarises all the input variables used in calculating the operating cost as well as briefly describing each.

Table 3-6: Input variables used in calculating operator cost

Variable	Description
Vehicle operator salary	• The monthly salary of a minibus taxi operator is R20 000,00.
Tyres and other expendables	• Contingencies and the cost of tyres per month makes up this cost category and amounts to a total of R5 735,00.
Vehicle maintenance	• The cost of maintaining a minibus taxi over a month period totals R4 303,00 per month.

Variable	Description
Facility maintenance	• The only cost included in the facility maintenance cost bracket is the cost to rent the premises where the minibus taxis are stored which totals R811,00 per month.
Administrative costs	• The administrative costs are made up of an unemployment insurance fund, a cell phone payment, and a bookkeeping cost, which amounts to R1 168,00 per month.
Supervision and control centre	• Satellite tracking and the cost of the vehicle license are the two main components of the supervision and control centre cost adding up to a total of R1 104,00 per month.
Fuel cost	• The cost of fuel, per litre, was taken as R16.48, the price as at the 1st of June 2019 (Automobile Association, 2019).
Fuel consumption	• The travelling consumption for fuel for private vehicles and minibus taxis were chosen as 7 *l*/100km and 12 *l*/100km respectively (Automobile Association, 2013; Hill, 2017).
Fuel idling	• The idling fuel for private vehicles and minibus taxis were taken as 1.2 *l*/hour and 1.5 *l*/hour respectively.
Vehicle-Hours	• The number of hours travelled that a minibus taxi travelled in a month. This value is used to determine the vehicle-hour cost of a minibus taxi. • This variable will be varied for the purpose of the sensitivity analysis.
Vehicle-Distance	• The distance that the average minibus taxi operator travels in a month. This value is used to determine the vehicle-distance cost of a minibus taxi. • This variable will be varied for the purpose of the sensitivity analysis.
Fraction of vehicle maintenance	• It is assumed that the cost of vehicle maintenance is not only a function of distance travelled but also of time spent driving. • A factor of 0.5 is used to compensate for the maintenance due to time spent driving such that time spent driving and distance driven are both factors that contribute to vehicle maintenance cost.

The environmental impact will also be considered by taking the amount of carbon dioxide emitted per litre of petrol consumed as 2.35 kg/l (Natural Resources Canada, 2014).

3.6.4 Construction Cost

The construction costs, as enumerated by del Mistro and Aucamp (2000) in their research *"Development of a public transport cost model"* is summarised in Table 3-7. These values were used to determine the capital costs of each form of infrastucture.

Table 3-7: Input variables used in calculating construction cost

Variable (Unit)	Value
Cost of way (Rm/lane-km)	1.045
Land cost - CBD/Commercial (Rm/lane-km)	0.875
Land cost - Outer section (Rm/lane-km)	0.23
Land cost – Residential (Rm/lane-km)	0.105
Minimum cost of station/stop (Rm)	0.4
Life of terminals (years)	20

3.6.5 Sensitivity Analysis Input Variables

Table 3-8 shows the variable inputs that were used for the preliminary outputs to be generated by the model. The values will subsequently be varied in a sensitivity analysis to determine the magnitude of the effects that these inputs have on the model outputs.

Table 3-8: Model variable inputs and values used

Variable	Value used	Description
Length of corridor	1 km	• A 1-kilometre corridor length was chosen as a base scenario from which to expand the model.
Ratio of minibus taxi occupancy to private vehicle occupancy	18:1.5	• Minibus taxis were assumed to be full and private vehicles were occupied by an average of 1.5 passengers.
Passenger handling time for minibus taxis	8 seconds per passenger	• Minibus taxi observations, based on video footage recorded along the Lynwood corridor in Pretoria, determined that it takes, on average, 8 seconds for a passenger to board and alight a taxi.
Percentage of minibus taxis stopping	50%	• Minibus taxi observations determined that on average half of the vehicles would stop to pick up or drop off a passenger at an informal stop.
Minibus taxi vehicle-hours	264 hours	• The value was obtained by assuming a minibus operator works 22 days per month and 12 hours a day.
Minibus taxi vehicle-distance	18 000 kilometres	• The value obtained from Taxi Recapitalisation Viability Model (Department of Transport, 2008)

3.7 MODEL OUTPUT VARIABLES

3.7.1 Signalised Intersection Design

The two main outputs required in the design of the signalised intersection are the effective red time and the effective green time. These variables will be used to determine the waiting time at the intersection and the flow of vehicles through the intersection respectively. The variables and their descriptions are summarised in Table 3-9.

Table 3-9: Output variables used in the signalised intersection design

Variable	Description
Effective red time in seconds	• The effective red time is the time during which a traffic movement is not effectively utilising the intersection. • The value is calculated using the following equation: $d_{avg} = \frac{r^2}{2C(1-{}^{v}/_{s})}$ (10) Rearranging the equation in terms of r: $r = \sqrt{d_{avg} \cdot 2C \cdot (1 - {}^{v}/_{c})}$ (11)
Effective green time in seconds	• The effective green time is the time during which a traffic movement is effectively utilising the intersection. • The value is calculated with the following equation: $\boldsymbol{g = C - r}$ (12)

3.7.2 User Cost

The user cost, in the case of the 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. The user cost for calculation for cars is the same as that of minibus taxis except service time is excluded.

The output variables considered in this section of the model is described in Table 3-10.

Table 3-10: Output variables used in calculating user cost

Variable	Description
Estimated service time	• Depending on the form of infrastructure, the service time will be calculated accordingly. • In the case of the curb-side taxi stop and the queue-bypass lane, the minibus taxis will make their stop according to the following equations which were adapted from the equations determining the service time for buses: $T_s = T_d + T_m \qquad (13)$ $T_d = c + \left\{ \sum_{h=1}^{m} a_h + \sum_{q=1}^{n} b_q \right\} + t_{we} + t_{wl}$ $\quad = T + t_{we} + t_{wl} \qquad (14)$ $T_m = t_e + t_l \qquad (15)$ Where: T : Bus dwell time at bus stop a_h : Consumed time of each passenger h for boarding b_q : Consumed time of each passenger q for alighting m : Number of boarding passengers n : Number of alighting passengers C_d : Time for opening and closing doors T_s : Service time at the bus stop T_d : Dwell time in and/or out of the bus stop T_m : Time in which buses move in and out of the bus stop t_{we} : Time in which buses wait to enter the bus stop t_{wl} : Time in which buses wait to leave the bus stop t_e : Time in which buses enter the bus stop t_l : Time in which buses leave the bus stop • For the remaining three forms of infrastructure, namely, the queue-jumping lane, the single lane pre-signal strategy, and the dedicated taxi lanes, the minibus taxis will pick up and drop off passengers during the red phase of the traffic cycle. The number of passengers that can be picked up and dropped off will be modelled according to the time constraints.
Wait time at red	• The waiting time at the red phase of the intersection is the same value as the pre-set average delay experienced by each vehicle as determined in the input variables. • In the cases of the queue-jumping lane and the single lane pre-signal strategy, where the minibus taxis receive a pre-signal

Variable	Description
	advantage and then travel with the private vehicles normally, the wait time is calculated separately.
Acceleration and deceleration time	• The time taken for a vehicle to accelerate and decelerate at an intersection is assumed to be the same for both private vehicles and minibus taxis. • The following equation of motion was used to calculate this time in hours: $T_a = 2 \times \frac{\frac{\frac{Vf}{3.6}}{a}}{3600}$ (16) Where: Vf : Final velocity (km/h) a : Acceleration/deceleration rate (m/s^2)
Travel time	• The travel time consists of the time a vehicle spends travelling at full speed for the relevant area chosen which is the distance of the corridor divided by the speed as well as the time taken to accelerate and decelerate.
User cost	• The user cost, finally, is the total travel time multiplied by the value of time for each income proportion of the respective transportation form.

3.7.3 Operator Cost

The operator cost for minibus taxis consists of the fuel cost, and the vehicle-time, -distance, and -fleet costs. For the private vehicle operator costs, two of the three variables, namely, the running cost and maintenance cost were obtained from the Automobile Association of South Africa. The final variable to calculate the operating cost of private vehicles is fuel cost.

The operating cost output variables are described in Table 3-11.

Table 3-11: Output variables used in calculating operating cost

Variable	Description
Fuel cost	• The fuel cost is the sum of the idling fuel cost and the travelling fuel cost. • The idling fuel cost is multiplied by the service time, in the case of the minibus taxis, and the waiting time at the red phase of the intersection.

Variable	Description
	• The travelling fuel cost is multiplied by the length of the section of road corridor being considered.
Vehicle-time cost for taxis	• The total time-dependent cost for a minibus taxi is divided by the total number of hours travelled during a 1-month period and multiplied by the number of hours it would take a taxi to travel the length of the corridor. • The time-dependent costs include vehicle operator cost, and vehicle maintenance cost.
Vehicle-distance cost for taxis	• The total distance-dependent cost for a minibus taxi is divided by the total number of kilometres travelled during a 1-month period and multiplied by the length of the corridor in consideration. • Tyres and other expendables, and vehicle maintenance make up the distance-dependent cost.
Vehicle-fleet cost for taxis	• The total fleet-dependent cost for a minibus taxi is divided by the fleet size which, for the sake of this model, was kept at 1. • Facility maintenance, administration, and supervision and control centre make up the cost for the vehicle-fleet category. • The vehicle-fleet cost was converted to a rate per hour and then multiplied by the number of hours it would take a taxi to complete the route.
Running cost for cars	• A value of R3.74/km was used to determine the running cost (Automobile Association, 2013).
Maintenance cost for cars	• The maintenance cost was calculated using the value of R0.40/km (Automobile Association, 2013).
Operating cost	• The total operating cost is obtained by finding the sum of the relevant values.

Variable	Description
Environmental cost	- The fuel consumption multiplied by the amount of carbon dioxide emitted per litre of fuel consumed.

It is necessary to mention that the operating cost of that of the minibus taxis and the private vehicles are considered comparable with each other. The operator salary, maintenance of the taxi facility, administrative costs, and the costs to operate the administrative and control centre are all costs not associated with private vehicles and which raise the costs to operate a minibus taxi.

3.7.4 Construction Cost

The construction cost for the different forms of priority infrastructure was determined by using the input cost values, which included cost of way, land cost, and minimum cost of a stop, and multiplying it by the length of the road infrastructure. It is necessary to note that the single lane pre-signal strategy had no construction costs involved as an existing section of road would be utilised for its purpose.

The construction cost outputs that are considered in the model are summarised and described in Table 3-12.

Table 3-12: Output variables used in calculating construction cost

Variable	Description
Construction cost per hour	- The construction cost per hour reduces the total cost of the infrastructure to an hourly cost by dividing it by the design life in years, which has been converted into the equivalent hours.
Construction cost per one-way trip	- The cost of the infrastructure for a one-way trip takes the construction cost per hour and multiplies it by the time a minibus taxi takes to complete a one-way trip.

3.8 DISCUSSION

This chapter discussed the design methodology, design, and development process of the macroscopic mathematical models. The relevant inputs and desired outputs pertaining to the signalised intersection design, user cost, operating cost, and construction cost were described in detail. The required functionality of the model was incorporated as part of the design methodology to meet the objectives that were set out during the conceptual design phase. The functionality of the model was methodically tested such that logical and accurate outputs would be delivered. The analysis and discussion of the outputs delivered by the model are discussed in Chapter 4.

4 APPLICATION: MODEL OUTPUTS

The development of a simulation model provides the ability to test which inputs affect the high-level economic outputs in terms of paratransit operators, passengers, other road users, and society at large, and to what extent these inputs are significant. Preliminary results can be obtained from the model by using expected inputs from observed minibus taxi and mixed traffic behaviour as well as flow rates and time that a taxi operator spends working each month.

4.1 SIGNALISED INTERSECTION DESIGN OUTPUTS

The purpose of developing a traffic queueing model as part of the simulation model is to provide a means to estimate important measures of the performance of the intersection which includes the vehicle delay and the traffic queue lengths. The information obtained from the traffic queueing model is also used to determine the capacity of the intersection as well as the number of private vehicles and minibus taxis that travel through the intersection over an hour period.

A constant cycle time of 60 seconds was used to determine the intersection queueing diagram and an average delay of 12 seconds per vehicle, relating to a level of service of B, was used to calculate the duration of the effective green and red times. The arrival and departure lines were plotted using the rates determined from conducting traffic counts along a busy corridor in Pretoria. The arrival rate of private vehicles and minibus taxis as they correspond to various locations, namely, the CBD, an arterial, and a residential area at peak and off-peak times, are summarised in Table 4-1.

Table 4-1: Arrival rate of private vehicles and minibus taxis

Location	Private vehicle arrivals (veh/h)	Minibus taxi arrivals (veh/h)
CBD/Commercial in-peak	1273	350
Arterial in-peak	1965	94
Residential in-peak	985	225
CBD/Commercial off-peak	634	144
Arterial off-peak	1364	42
Residential off-peak	534	81

The signalised intersection queueing graph that applies to the curb-side taxi stop intersection is illustrated in Figure 4-1. The cycle length is based on the 60 seconds chosen at the start of the modelling process and the red time is calculated using equation 11:

$$r = \sqrt{d_{avg} \cdot 2C \cdot (1 - {}^{v}/_{c})}$$

The observations and outputs from the queueing graphs were obtained from Excel where the calculations were conducted.

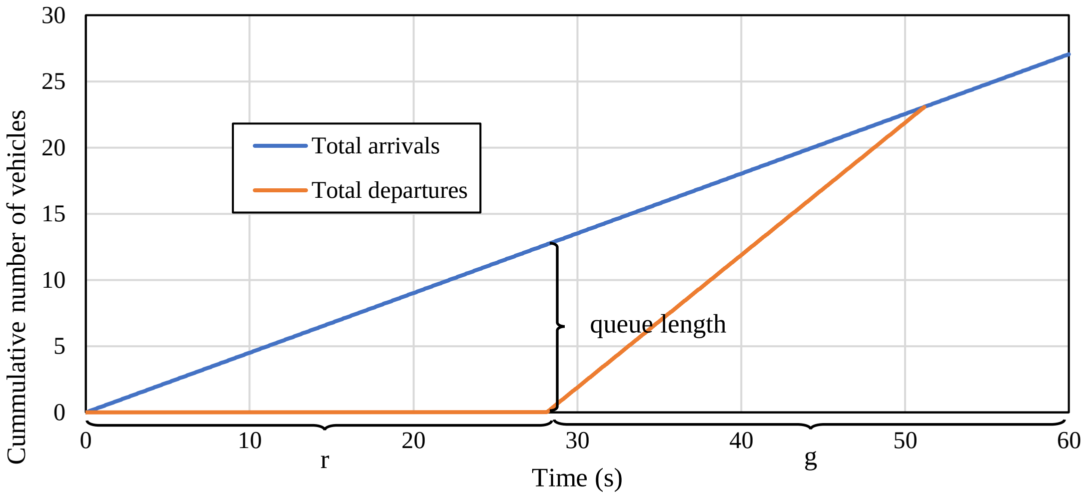


Figure 4-1: D/D/1 signalised intersection for the curb-side taxi stop intersection

The intersection for the curb-side taxi stop form of infrastructure causes the longest queue to form over the duration of the red (r) traffic cycle. Over the 28.1 second red cycle, a queue length of 12.7 vehicles form with a combination of private vehicles and minibus taxis. The entire queue dissipates after 51.2 seconds from the start of the red cycle or 23.1 seconds into the green (g) cycle. The intersection capacity, as is the case with all the queueing diagrams, amounts to 1913 vehicles per hour and is therefore able to accommodate all the traffic arrival rates as they were identified in different locations in the city except for the in-peak flow rate on an arterial road. This flow exceeds the intersection capacity by 197 vehicles per hour.

The intersection queueing diagram pertaining to the queue-jumping lane and the single lane pre-signal strategy is illustrated in Figure 4-2. The same design applies to both forms of infrastructure as their methods of providing minibus taxis with a pre-signal priority is similar.

In the first phase of the queueing diagram both the minibus taxi (t) and the private vehicle (c) queues start to build. The minibus taxis then receive a priority green after which they re-join the regular traffic as can be seen in the change in gradient of the “mixed-traffic arrivals” curve.

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 means that the delay for private vehicles would not be affected by the priority green phase.

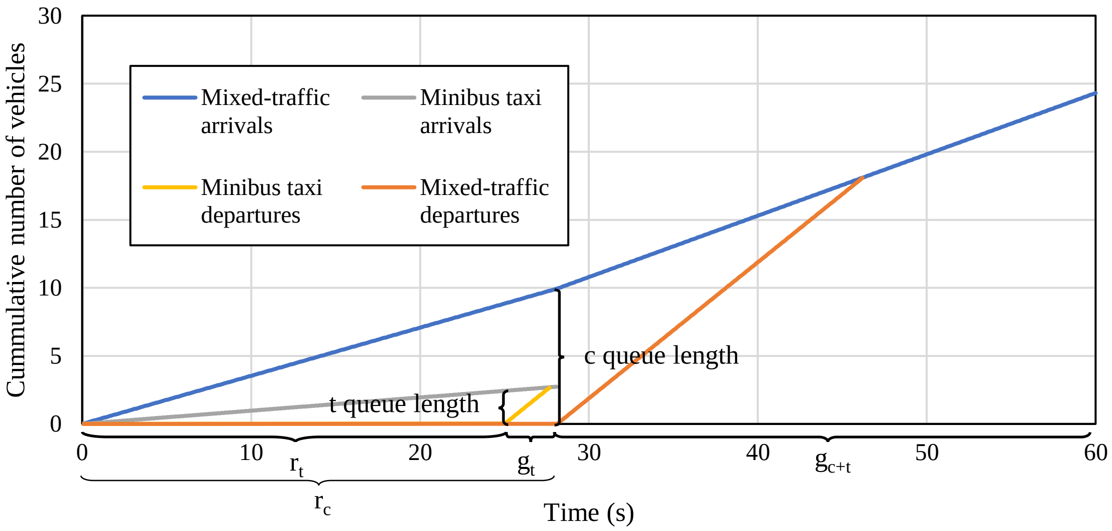


Figure 4-2: D/D/1 signalised intersection for the queue-jumping lane and the single lane pre-signal strategy intersections

Providing the minibus taxis with a pre-signal priority of 3.1 seconds effective green time allows an average of 2.7 taxis to skip the queue over each traffic cycle in both the case of the queue-jumping lane as well as the single lane pre-signal strategy. This amount of time is deemed sufficient to allow the queue of minibus taxis to dissipate. The length of the section of road on which the minibus taxis queue is designed to be at least 11 metres long which will accommodate the highest flow of these vehicles. At the end of the pre-signal priority the minibus taxis and private vehicles travel in the same lane as the stream of mixed traffic. This results in an increase in traffic flow at 28 seconds into the cycle. The entire queue dissipates after 46.2 seconds which is 5 seconds shorter than in the case of the curb-side taxi stop.

The delay that private vehicles experience over the duration of a traffic cycle is 12 seconds per vehicle and this value was kept constant over all modes of infrastructure. The minibus taxi delay, however, varied due to the pre-signal priority: over the duration of the red cycle, the delay was 12.3 seconds per taxi but after the pre-signal phase ends, the delay per taxi drops to 5.1 seconds. This is due to minibus taxis joining the mixed traffic once the queue has started dissipating. The delay is calculated by finding the area under the curve in both cases. This is done with the use of Excel. This value is then divided by the number of vehicles passing the intersection over that time to find the average delay of each vehicle.

The queue-bypass lane and the dedicated taxi lane intersection queueing graph is illustrated in Figure 4-3. Due to the queue-bypass lane featuring on both sides of the intersection, the queue formation and subsequent dissipation of the traffic is similar to that of the dedicated taxi lane.

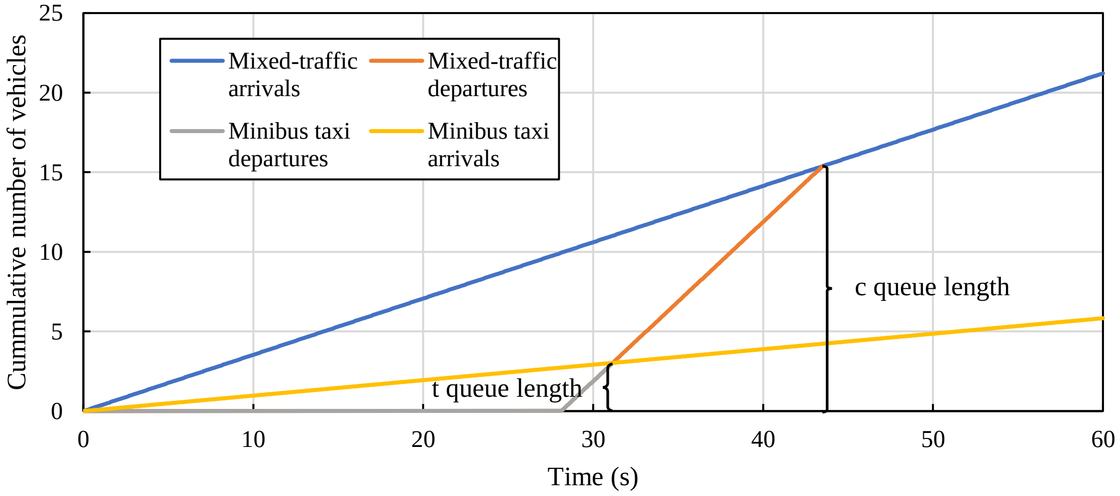


Figure 4-3: D/D/1 signalised intersection for the queue-bypass and dedicated taxi lane intersections

The intersection has two lanes associated with the transit infrastructure and, as a result, doubling the capacity of the intersection. Despite the increased capacity of the intersection, the in-peak flow rate on an arterial road still exceeds the capacity of the road by 52 vehicles per hour. In the case of the minibus taxi flow, the flow is well below the capacity of the intersection. The private vehicle traffic queue of an average of 10 vehicles dissipates after 47 seconds whereas the minibus taxi queue of 3 vehicles per cycle dissipates after 31.1 seconds. With both modes of transportation, the average delay per vehicle per cycle is 12 seconds.

4.2 COST OUTPUTS

This chapter summarises the outputs delivered by the simulation model across the five forms of transit infrastructure as well as applying them to the three main road types in a city at in-peak and off-peak times. The outputs include travel time, user cost per hour, maximum number of passenger transfers per hour, operating cost per hour, fuel cost per one-way trip, construction cost, total cost per hour, and the total carbon dioxide emissions produced over a one-way trip.

4.2.1 Travel Time

The travel time comparisons between minibus taxis and private vehicles across the five forms of transit infrastructure are illustrated in Figure 4-4. The vertical axis indicates the time taken to complete a one-way trip of one kilometre.

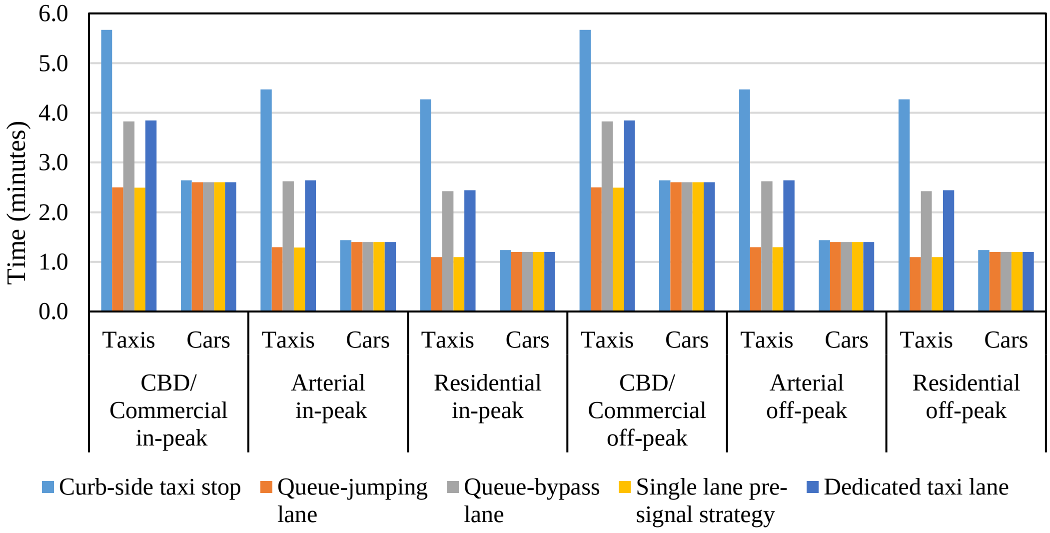


Figure 4-4: Travel time comparison between minibus taxis and private vehicles

Considering the CBD/commercial in-peak route, the most significant decrease in travel time was observed when comparing the curb-side taxi stop to the queue-jumping lane and the single lane pre-signal strategy which both resulted in a 56% decrease equating to a faster travel time of 3.2 minutes. The queue-bypass lane and the dedicated taxi lane reduced travel time by 33% or 1.8 minutes along the corridor. The queue-jumping lane and single lane pre-signal strategy are the most successful in saving time for minibus taxi operators which is attributable to the priority green phase that they receive over each cycle. At the end of the dedicated green phase the minibus taxis travel with the mixed traffic but the delay that they experience over the all-green phase is significantly smaller than what they would have experienced had such a priority not been granted.

In the case of private vehicles, there is a 1% decrease in travel time when comparing all the transit infrastructure forms to that of the curb-side stop. This is due to the delay that minibus taxis cause when they decelerate to enter the curb-side bay which is not the case for the remaining four transit infrastructure forms.

When considering the three different locations in the city, the CBD/commercial corridor has the longest travel time, followed by the arterial and the residential corridor. The travel times correspond to the average speed inputs used in the model and there are no fluctuations between the transit modes across the three city locations that do not correspond to the changes already discussed.

From these results a decision could be made as to where to implement which form of infrastructure: to reduce travel time, particularly for the minibus taxis, it would be the most logical to construct the single lane pre-signal strategy in a part of the city where the travel time is high, like on a CBD/commercial corridor. Building the queue-jumping lane or the queue-bypass lane on a corridor in the CBD would be logistically challenging as increasing the width of the road would be very costly and for this reason the single lane pre-signal strategy would be ideal. An arterial corridor might be able to accommodate the queue-jumping lane as well as the queue-bypass lane and such infrastructure would be well suited to reduce the travel times along such a corridor. Finally, the dedicated taxi lane can be constructed or implemented in any of the three city locations, the only prohibitive factor would be the construction cost which will be discussed later in this chapter.

4.2.2 User Cost per Hour

The comparison in user cost per hour between minibus taxis and private vehicles across the five forms of transit infrastructure are illustrated in Figure 4-5. This considers the total cost of all passengers that are transported along the corridor.

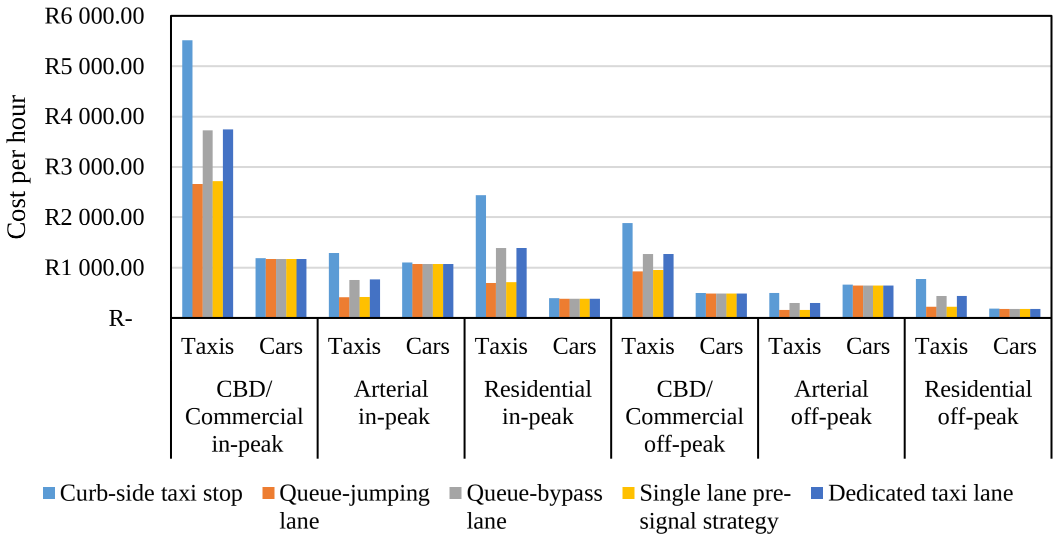


Figure 4-5: User cost per hour comparison between minibus taxis and private vehicles

The outputs from the user cost comparison correlates with the outputs obtained from the travel time comparison in that the queue-jumping lane and the single lane pre-signal strategy show the greatest decrease in user cost per hour when compared to the curb-side taxi stop across all locations that were modelled. The decrease ranges between 41% and 72% when the infrastructure forms are compared to their respective curb-side taxi stops.

The user cost is not only affected by the travel time but also by the number of passengers travelling on the route – more passengers equate to a greater total value of time. This explains the decrease in user cost over the corridor locations, with less passengers being transported the user cost greatly decreases. There is a 77% decrease in the minibus taxi user cost when considering the curb-side stop along an arterial corridor in the peak period compared to a CBD/commercial corridor in the peak period, or a difference of R4 228.66. When the base case is compared to an arterial corridor at an off-peak period there is a 91% decrease in user cost or a difference of R5 020.18. The output from the private vehicle traffic corresponds to the arrival rate at the intersection and there are no significant fluctuations across the five different transit modes.

4.2.3 User Cost per Passenger per Trip

The results from Figure 4-5 are reduced to a user cost per passenger per trip by dividing the total hourly user cost by the number of traffic arrivals per hour and the vehicle occupancy which is 18 and 1.5 for minibus taxis and private vehicles respectively. Figure 4-6 illustrates these results.

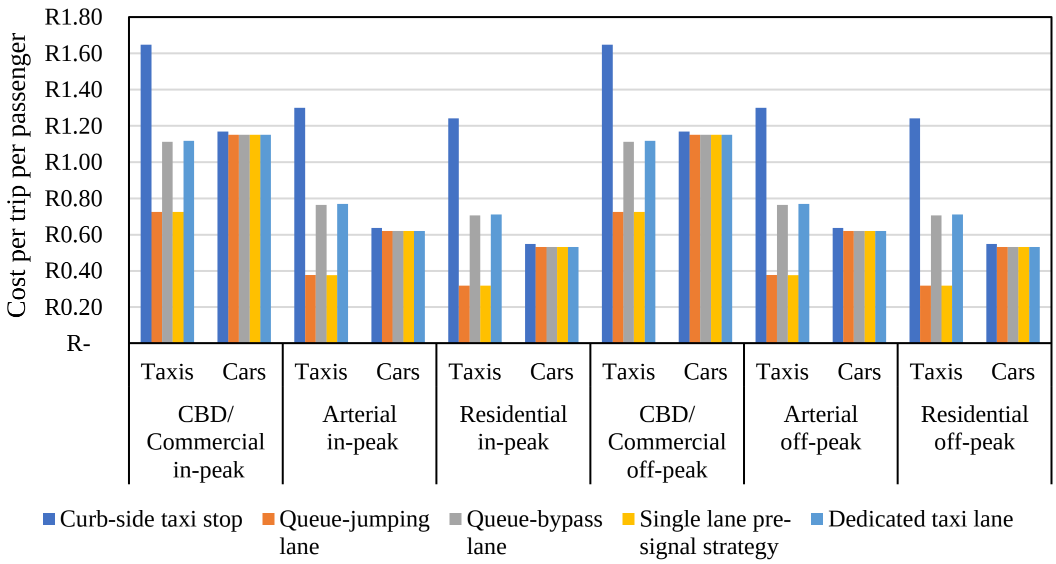


Figure 4-6 User cost per passenger per trip comparison between minibus taxis and private vehicles

The value of time for private vehicle users, as discussed earlier, is significantly greater than that of a minibus taxi passenger comparing at R26.57 and R13.36 per passenger respectively. Including the value of time for different income groups, however, is necessary to compile an economic model that reflects the situation accurately. In the case of the arterial corridor in the peak period and in some of the cases in the off-peak period, when the user cost per hour is considered, the user cost of the private vehicles exceeds that of the minibus taxis. When these values are reduced to a cost per passenger per trip, the results become clearer: in all locations where a taxi curb-side stop is implemented, the minibus taxi user cost exceeds the cost of the private vehicle user cost. When the other transit infrastructure forms are considered, the difference in user cost per passenger greatly decreases, and in some cases reverses: for the queue-jumping lane and single lane pre-signal strategy, the minibus taxi user cost is R0,24 lower than the private vehicle user cost. This needs to be taken into consideration when deciding which forms of infrastructure to implement and to what extent it will be successful.

It is also necessary to note the maximum number of passengers that can board or alight a minibus taxi in an hour for each infrastructure mode: the dedicated taxi lane, the curb-side taxi stop, and the queue-bypass lane allow for the greatest number of boarding or alighting of passengers in an hour. This is due to no limitations being set on the time that a minibus has to stop and pick up and drop off passengers. The remaining two priority infrastructure modes, the queue-jumping lane and the single lane pre-signal strategy, allow far fewer passengers to board or alight in an hour. These two forms of infrastructure are limited by the amount of time a minibus taxi has to pick up and drop off a passenger during the red cycle phase. The number of passengers that can board or alight a taxi in an hour is summarised in Table 4-2.

Table 4-2: Maximum boarding or alighting of passengers in an hour

Curb-side taxi stop	Queue-jumping lane	Queue-bypass lane	Single lane pre-signal strategy	Dedicated taxi lane
1674	28	1674	33	1674

4.2.4 Operating Cost per Hour

The operating cost per hour of travel for minibus taxis and private vehicles is illustrated in Figure 4-6.

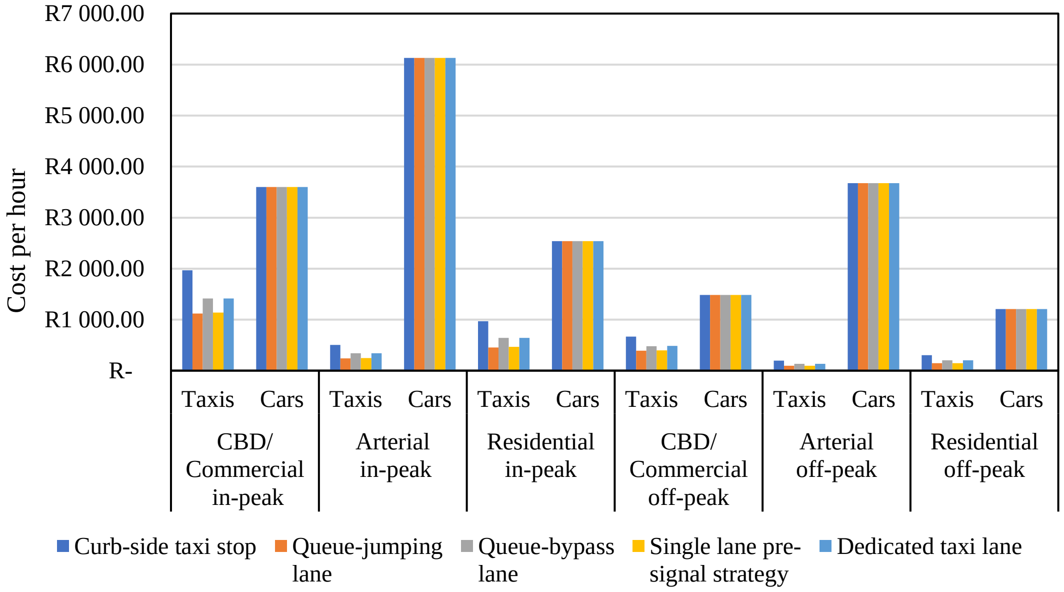


Figure 4-7: Operating cost per hour comparison between minibus taxis and private vehicles

The operating cost for both minibus taxis as well as private vehicles are functions of time, distance, and vehicle arrival rate. Since the distance was not varied in the base scenario of the model, travel time and frequency of vehicles travelling along the route are directly related.

As observed in the previous two outputs of the model, the travel time of private vehicles does not vary in any of the five transit infrastructure forms. The change in operating cost arises with the change in location of the transit scenario. There is a 70% increase in operating cost per hour when the CBD/commercial in-peak scenario feature is compared to the arterial in-peak counterpart and a decrease in 67% when it is compared to the residential off-peak scenario due to the greater number of vehicles travelling along the corridor. These costs, however, cannot be reduced since the transit priority infrastructure does not offer any financial benefit to private vehicle users.

The minibus taxi operating cost sees a 51% decrease when the curb-side stop is compared to the queue-jumping lane and a 50% decrease when it is compared to the single lane pre-signal strategy. When the curb-side stop is compared to the queue-bypass lane and dedicated taxi lane, a 34% and 35% decrease in operating cost is observed respectively. All four of the transit priority infrastructures provide a significant monetary benefit to minibus taxi operators and the cost to operate the vehicle along each infrastructure form was quantified by considering the travel time as the only factor that affects the hourly operating cost per minibus taxi.

The cost for a minibus taxi to travel the base 1-kilometre route using the five infrastructure forms is summarised in Table 4-3.

Table 4-3: Minibus taxi operating cost per 1-kilometre trip

Infrastructure	Operating cost/vehicle	Savings compared to curb-side taxi stop
Private vehicle	R5.32	-
Curb-side taxi stop	R10.58	-
Queue-jumping lane	R5.49	48%
Queue-bypass lane	R7.60	28%
Single lane pre-signal strategy	R5.48	48%
Dedicated taxi lane	R7.62	28%

The minibus taxi operating costs exceed that of the private vehicles by between R0.16 and R5.26 for the single lane pre-signal strategy and the curb-side taxi stop respectively. The travel time that the four forms of infrastructure save when compared to the curb-side taxi stop amounts to between R2.96 and R5.10 with the single lane pre-signal strategy again providing the most benefits to minibus taxi operators. When these monetary values are compounded by the frequency of taxis travelling along the corridor and the total distance that the operators travel in a day, they can provide significant monthly savings for both taxi owners as well as operators.

Considering the inputs of the base scenario of a minibus taxi operator working 264 hours in a month, the results summarised in Table 4-4 are obtained pertaining to the monthly savings due to the priority infrastructure.

Table 4-4: Monthly savings per minibus taxi with each infrastructure form

Infrastructure	Savings cost/taxi	Trips/month	Monthly savings/taxi
Queue-jumping lane	R5.09	6 345	R32 298
Queue-bypass lane	R2.98	4 141	R12 340
Single lane pre-signal strategy	R5.10	6 352	R32 396
Dedicated taxi lane	R2.96	4 120	R12 197

The cost in savings that a minibus taxi operator can make, when driving along the same corridor for the entire month can amount to over R32 000 in the case of the queue-jumping lane and single lane pre-signal strategy or over R12 000 for the queue-bypass lane and dedicated taxi lane. It should be noted that this is an idealised situation. This does, however, make a strong case for the implementation of these infrastructure forms on busy corridors as it is clear that significant monthly savings would be one of the biggest benefits to adopting this solution.

4.2.5 Fuel Cost

The fuel cost, as it is a large contributing factor to the operating cost of both private vehicles and minibus taxis, was evaluated separately. The fuel cost per one-way trip for minibus taxis and private vehicles is illustrated in Figure 4-8.

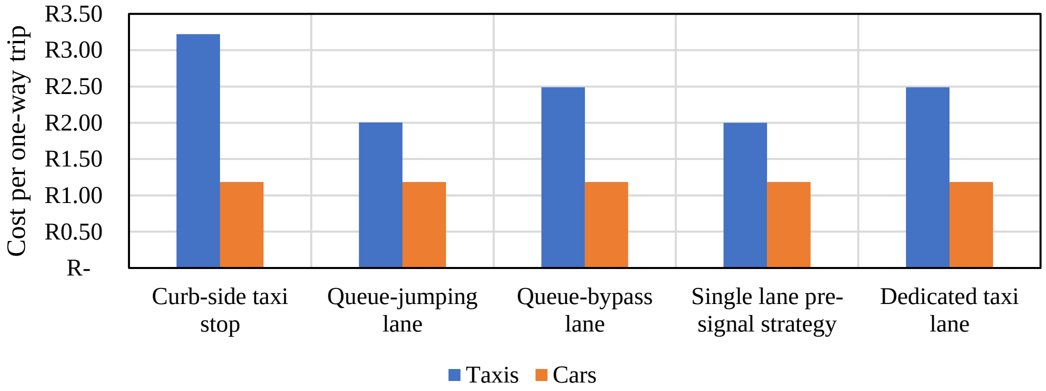


Figure 4-8: Fuel cost per one-way trip comparison between minibus taxis and private vehicles

The cost of fuel per trip for mixed-vehicle is constant over all five forms of infrastructure at R1.18. The cost for minibus taxis, however, differ due to the time spent idling being the main cause for the fluctuations in fuel cost. The fuel cost per trip decreases by 38%, or R1.22, when the curb-side taxi stop is compared to both the queue-jumping lane as well as the single lane pre-signal strategy. A 23% reduction in fuel cost, or a decrease of R0.73 per trip, is observed when the curb-side taxi stop is compared to the queue-bypass lane and the dedicated taxi lane.

4.2.6 Environmental Cost

Naturally, the reduction in fuel used by the minibus taxis means that the impact on the environment would also decrease. Figure 4-9 illustrates the carbon dioxide emissions, denoted by CO_2-e, that is emitted from travelling along the corridor for each infrastructure form.

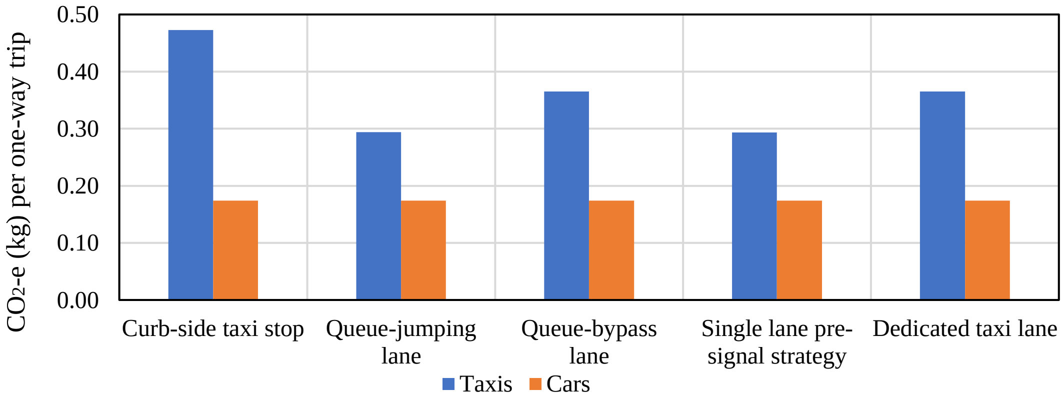


Figure 4-9: Carbon dioxide emissions per one-way trip comparison between minibus taxis and private vehicles

Since the only emissions considered in the model are due to the burning of fuel, the carbon dioxide emissions produced are directly related to the fuel consumption with the curb-side taxi stop being the largest contributor to carbon dioxide emissions and the queue-jumping lane and the single lane pre-signal strategy being the smallest. Private vehicles produce less emissions than minibus taxis over all five of the infrastructure forms but when the number of passengers is considered, the carbon dioxide emissions per passenger are greatly reduced for the minibus taxis. Assuming a full minibus taxi and private vehicle of 18 and 5 occupants respectively, the emissions produced per passenger per trip for the minibus taxi ranges between 0.015 kg and 0.025 kg. The emissions emitted per trip per passenger for the private vehicles, by contrast, is 0.035 kg.

4.2.7 Construction Cost

The construction costs for the five forms of transit infrastructure are illustrated in Figure 4-8.

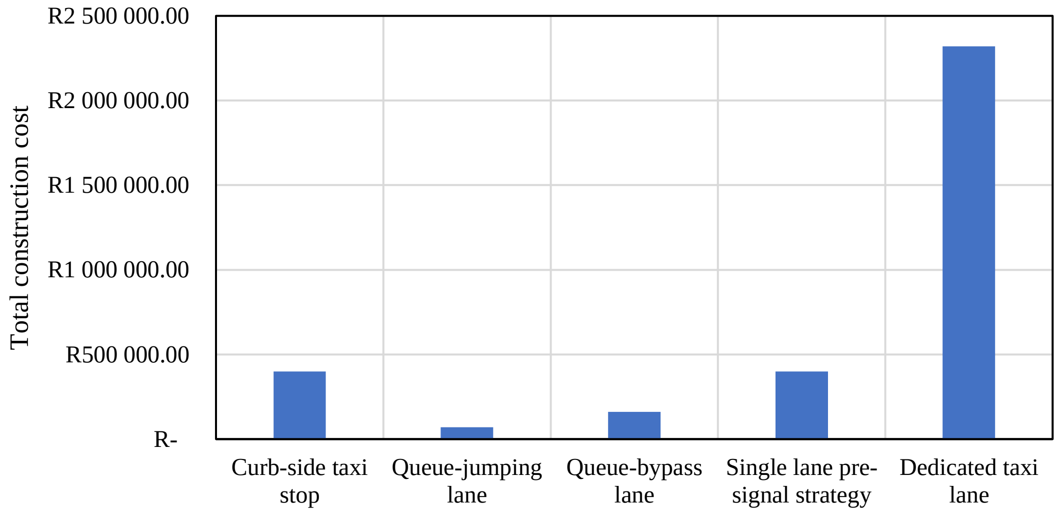


Figure 4-10: Construction cost comparison between the forms of infrastructure

The dedicated taxi lane incurs the greatest construction cost, which includes the cost to construct a curb-side stop, cost of land, and road construction cost amounting to R2 320 000. The remaining four transit infrastructure forms are significantly less expensive: the curb-side taxi stop costs R400 000 which includes paving, signage and road markings. The queue-jumping lane consists only of a short section of road of 11 m with a passive taper. The queue-bypass lane consists of two road sections, one with an active taper and one with a passive taper and, as with the queue-jumping lane, the length is determined according to the vehicle arrival rate at the intersection and the location of the infrastructure. In the case of the CBD/Commercial location, the passive taper is 7 m in length and the active taper is 7 m as well. The lengths are calculated based on the number of minibus taxis that queue over the red phase of the traffic cycle and, in the case of the queue-bypass lane, the distance a minibus taxi requires to accelerate to the appropriate speed to safely join the mixed traffic. Finally, the single lane pre-signal strategy incurs the same cost as the curb-side taxi stop based on the assumption that some costs will be incurred when constructing an island in the middle of the road onto which passengers can safely alight from the taxi or board onto.

4.2.8 Total Cost per Vehicle and per Passenger

The total cost per one-way trip for minibus taxis and private vehicles is illustrated in Figure 4-11.

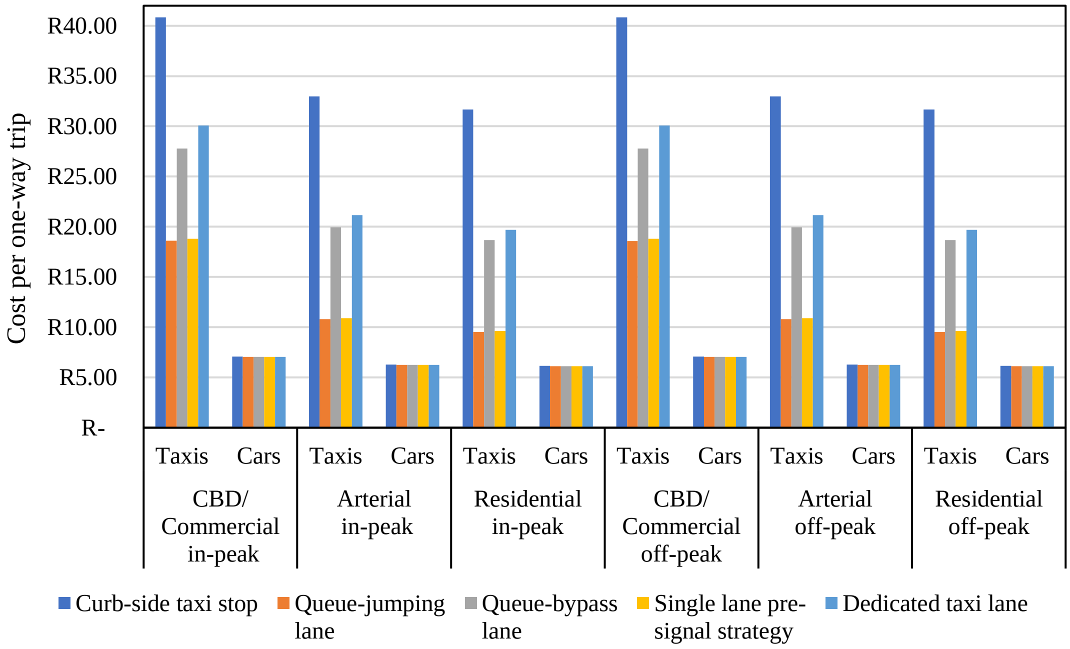


Figure 4-11: Total cost per vehicle per one-way trip comparison between minibus taxis and private vehicles

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.

The total cost per passenger per one-way trip for minibus taxis and private vehicles is illustrated in Figure 4-12.

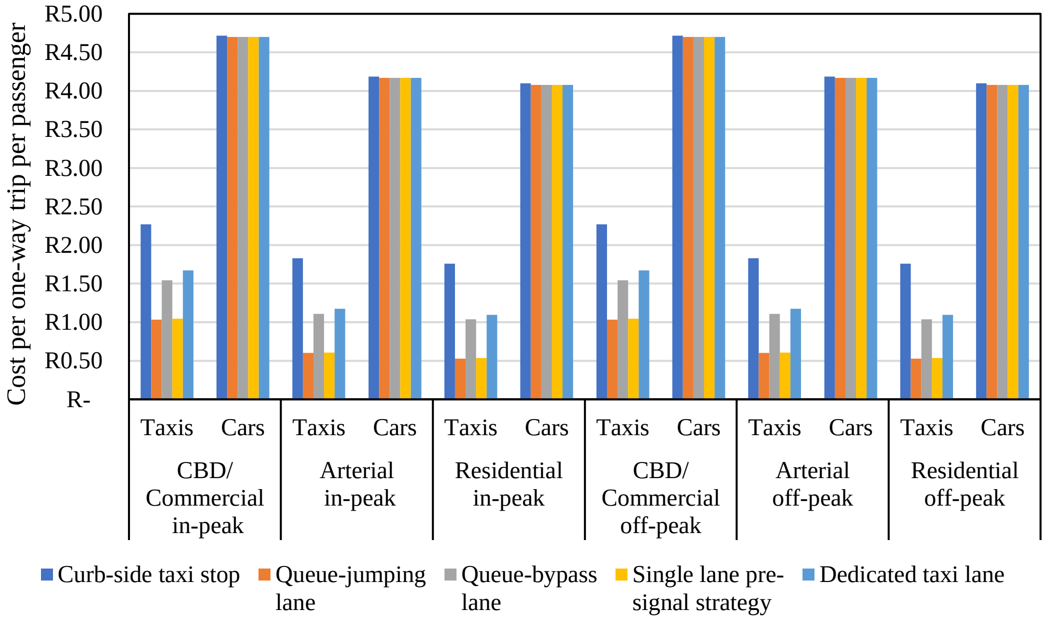


Figure 4-12: Total cost per passenger per one-way trip comparison between minibus taxis and private vehicles

When the cost per passenger is considered, it becomes clear that the total cost per trip for minibus taxis is significantly less than that of private vehicles. The trends in cost between each transit measure is the same as the cost per vehicle-trip comparison but a more holistic set of results is gained from considering the cost per passenger. When considering the CBD/Commercial location, the cost per trip ranges between R1.04 for the single lane pre-signal strategy, and R2.27 for the curb-side taxi stop. The cost for a passenger-trip in a private vehicle is R4.72.

Finally, the number of passengers that can be transported per hour on each of the forms of infrastructure needs to be discussed. Table 4-5 summarises the passenger capacities for each of the forms of infrastructure when implemented at the three different locations.

Table 4-5: Passenger capacities for the different forms of transit infrastructure

	Curb-side taxi stop	Queue-jumping lane	Queue-bypass lane	Single lane pre-signal strategy	Dedicated taxi lane
CBD/ Commercial in-peak	3347	3671	3347	3746	3347
Arterial in-peak	992	1079	992	1099	992
Residential in-peak	1963	2171	1963	2219	1963
CBD/ Commercial off-peak	1141	1274	1141	1305	1141
Arterial off-peak	383	422	383	431	383
Residential off-peak	618	693	618	711	618

The single lane pre-signal strategy is the transit infrastructure form that allows the greatest number of passengers to be transported by minibus taxi. This is followed by the queue-jumping lane. The curb-side taxi stop, queue-bypass lane, and the dedicated taxi lane all three have the lowest passenger capacity. The priority green phase that minibus taxis receive in the single lane pre-signal strategy and the queue-jumping lane is the reason for the increased capacity. The average arrival rate of minibus taxis at an intersection should be measured before deciding on which infrastructure to implement.

4.3 SENSITIVITY ANALYSIS

A sensitivity analysis is the study to measure what impacts fluctuations certain parameters would have on the outputs of a mathematical model or system. In the case of this model, six input parameters are varied, one at a time, using predetermined ranges, whilst assuming all the other parameters remain constant. This method is also referred to as one-at-a-time analysis. By conducting the analysis, it is possible to achieve a good overview of the most sensitive components of the model and specifically to distinguish between high-leverage variables that have a significant impact on the model, and low-leverage variables that have minimal impact in the model (Ray et al., 2015; Balaman, 2019). Another application of the sensitivity analysis is to improve the model, serving as a method of calibration: discerning between the inputs that are most important to predictions and forecasts versus those that are not of importance and what observations are more or less important to the predictions and forecasts. This can lead to identifying problems in the data or model development which can subsequently be fixed.

Table 4-6 summarises the variables used in the sensitivity analysis and the ranges used. The purpose of the sensitivity analysis is to identify which of the variables identified, having the greatest level of uncertainty regarding their magnitudes, have the greatest impact on the model and what implications this could have.

Table 4-6: Variables and ranges used in the sensitivity analysis

Variable	Sensitivity range used
Length of corridor	1 – 9 (Increments of 2 km)
Ratio of minibus taxi occupancy to private vehicle occupancy	2:5 – 18:1 (Increments of +4:-1)
Passenger handling time for minibus taxis	2 – 12 (Increments of 2 seconds)
Percentage of minibus taxis stopping	0 – 100% (Increments of 20%)
Minibus taxi vehicle-hours	40 – 360 hours (Increments of 40 hours)

The first sensitivity analysis conducted, varying the length of the corridor between 1 and 9 kilometres, whilst keeping all the other variables constant, is illustrated in Figure 4-13. The location of the transit infrastructure and traffic flow was kept to the CBD/commercial region in the peak flow – this was done for all the transit forms of infrastructure. Although 7 outputs were generated by the model, it was decided to conduct the sensitivity analysis on the cost per passenger-trip only. This output is the most indicative of the functioning of the model and provides a holistic overview of all the outputs.

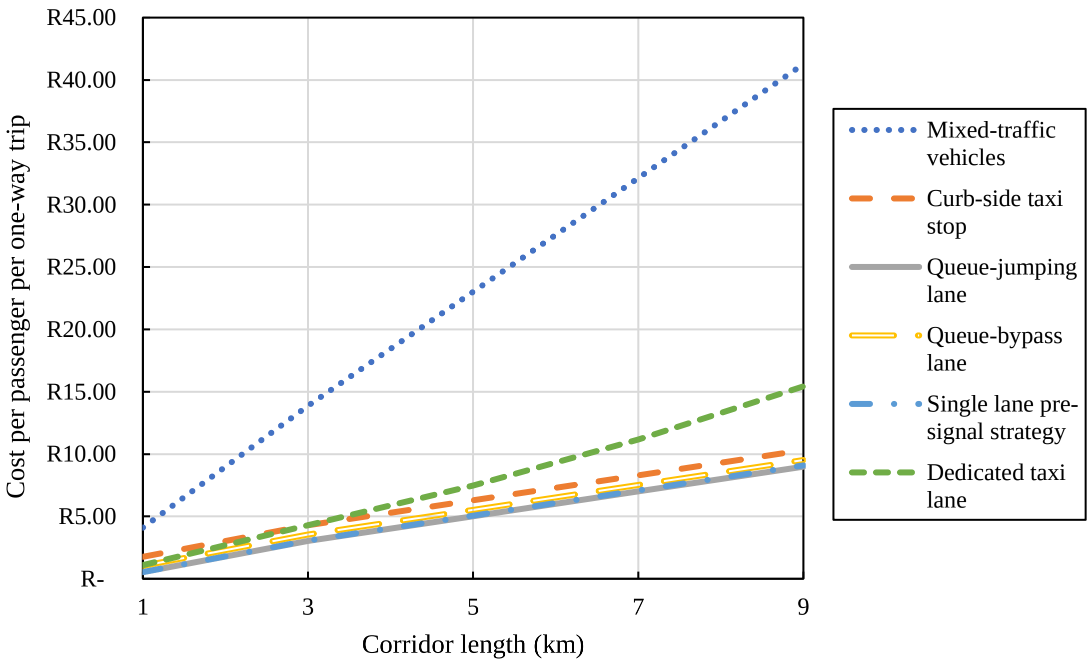


Figure 4-13: Cost per passenger per one-way trip with the increase in corridor length

Firstly, it is observed that all forms of infrastructure, including private vehicle cost, increases linearly with the increase in distance. The exception to this is the dedicated taxi lane cost per passenger trip which is greatly affected by the construction cost. The other forms of infrastructure do not increase with the increase in corridor length and this only increase as a result of travel time and distance which increases linearly.

All the outputs are highly sensitive to change in corridor length: the sensitivity ranges between 93% and 106% for the outputs of the curb-side taxi stop and the single lane pre-signal strategy respectively. The sensitivity is calculated by determining the change in the value of the y-axis and dividing it by the change in the value of the x-axis.

The total private vehicle cost per passenger shows the greatest increase in cost, ranging between R4.10 for a 1-kilometre trip to R41.26 for a 9-kilometre trip. Conversely, the queue-jumping lane incurs the lowers cost per passenger trip, ranging between R0.53 to R8.99. The dedicated taxi lane is the transit priority infrastructure with the most expensive total cost per passenger increasing to R15.43 for a 9-kilometre trip from R1.09.

The change in cost per passenger per one-way trip for the minibus taxis and private vehicles with the increase in the change in ratio of minibus taxi passengers to private vehicle passengers is illustrated in Figure 4-14.

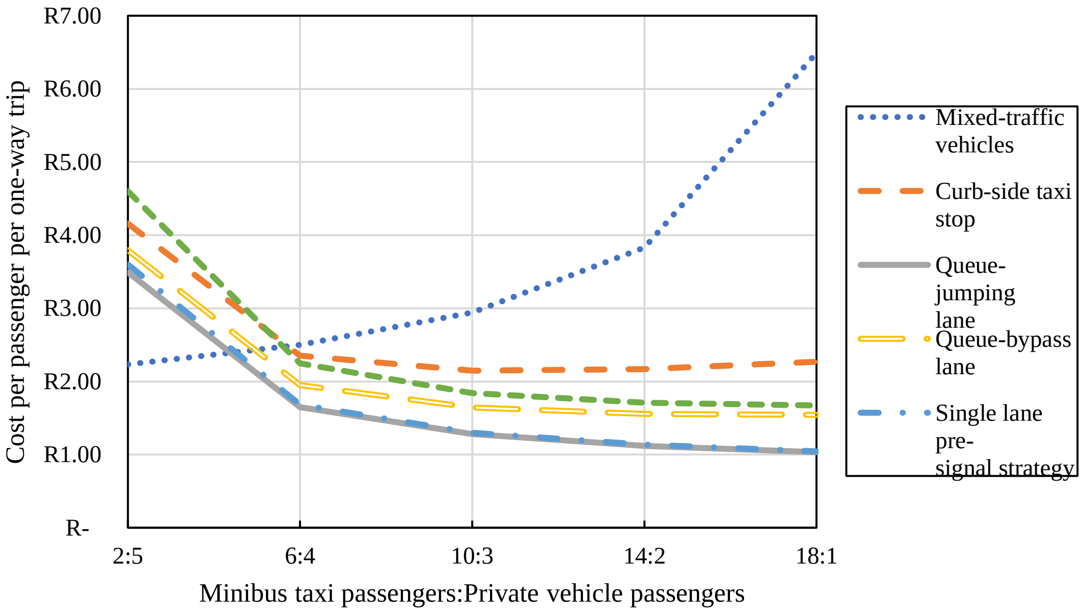


Figure 4-14: Cost per passenger per one-way trip with the change in ratio of minibus taxis to private vehicle passengers

There is a decrease in cost per passenger per one-way trip for private vehicles as the ratio of minibus taxi passengers to private vehicle passengers changes from 2:5 to 18:1. The converse is true regarding the hourly cost for minibus taxis. Mixed traffic vehicles have a 75% sensitivity as the ratio changes between the two boundaries. The queue-jumping lane and the single lane pre-signal strategy are the two infrastructure forms that are the least sensitive to the change in the number of passengers with a sensitivity of 61%. The curb-side taxi stop, by contrast, is significantly more sensitive to this change with a sensitivity of 80%.

From an economic point of view, the implementation of these forms of infrastructure should be considered necessary as the cost per passenger when a private vehicle is full amounts to R2.26 per 1-kilometre trip whereas, in the case of the curb-side taxi stop, a minibus taxi filled to capacity costs R2.38 per passenger trip. For the remaining transit infrastructure forms, a cost of R1.22 for the queue-jumping lane, R1.64 for the queue-bypass lane, R1.24 for the single lane pre-signal strategy, and R1.65 for the dedicated taxi lane is observed. The holistic economic cost of travel for a minibus taxi transporting 18 passengers when using a form of transit priority infrastructure, costs less than a private vehicle transporting 4 passengers. This reduction in cost can be achieved without causing a financial strain on private vehicle users.

The increase in cost per passenger per one-way trip with the increase in passenger handling time of the minibus taxis, which is measured in seconds, is illustrated in Figure 4-15.

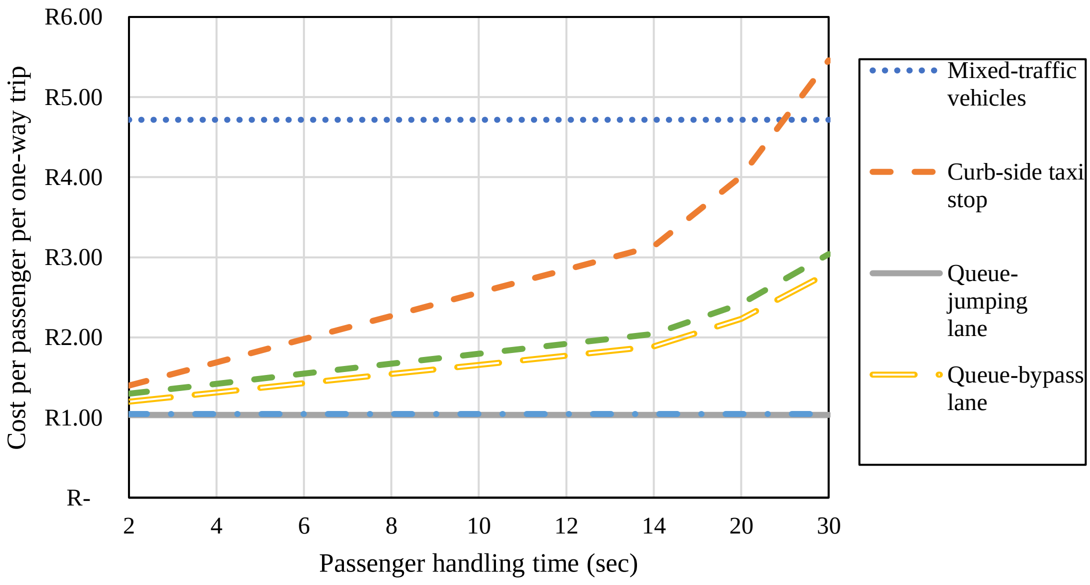


Figure 4-15: Cost per passenger per one-way trip with the increase in passenger boarding time of minibus taxis

Private vehicles have a 0% sensitivity when the cost per passenger-trip is compared to the passenger handling time in seconds. This illustrates that the time a minibus taxi takes to pick up or drop off a passenger has, in theory, no effect on other road users. In reality, however, minibus taxis often make informal stops which does cause congestion on the roads. The queue-jumping lane and the single lane pre-signal strategy also have a 0% sensitivity. This is due to minibus taxis using the red traffic cycle to pick up or drop off passengers for these two forms of transit infrastructure. As the passenger handling time decreases, less passengers will be able to board and alight a taxi, but it does not affect the travel time.

The curb-side taxi stop has the highest sensitivity of 65% followed by the queue-bypass lane and the dedicated taxi lane, both of which have a sensitivity of 43%. These infrastructure forms are dependent on the time a passenger takes to board and a minibus taxi as no time limit is put on how long a taxi must wait for passengers. This factor should be taken into consideration when deciding on the location of implementation. The passenger handling time was extended to determine at which value the cost per passenger-trip of the minibus taxi equals that of the private vehicle. It was found that at a handling time of 25 seconds the cost per passenger-trip for minibus taxis using the curb-side taxi stop equals the cost per passenger trip for private vehicles. The other infrastructure forms were all still significantly lower in cost.

Figure 4-16 illustrates the travel cost per passenger per one-way trip with the increase in the percentage of minibus taxis stopping to pick up or drop off passengers.

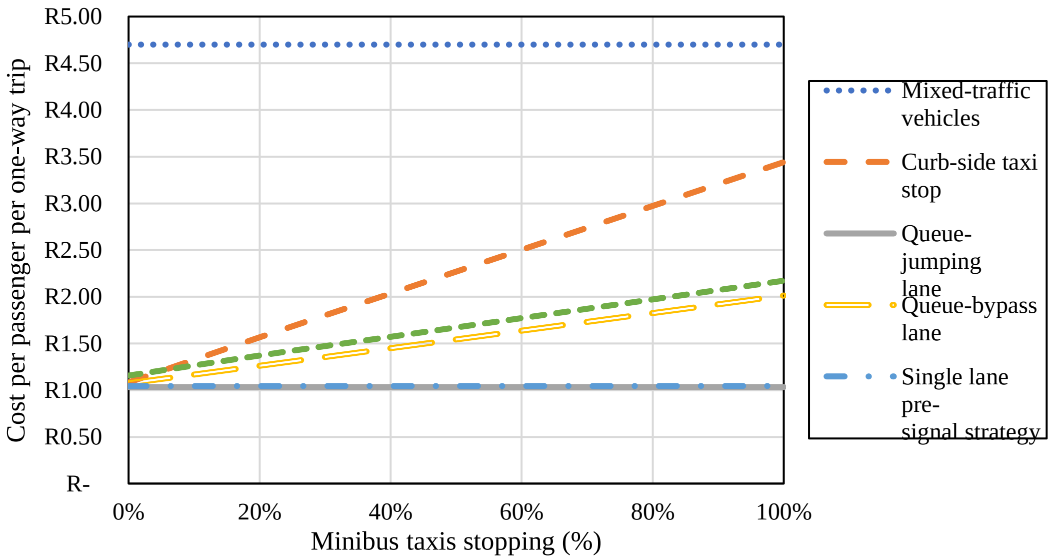


Figure 4-16: Cost per passenger per one-way trip with the increase in percentage of minibus taxis stopping

The total cost per passenger-trip for minibus taxis over all five infrastructure forms are lower than that of the total private vehicle passenger-trip cost. This is true even up to the point where 100% minibus taxis stop to pick up or drop off passengers. The curb-side taxi stop is the most sensitive to the percentage of minibus taxis stopping with a sensitivity of 69% or increasing from R1.08 per passenger-trip at 0% taxis stopping to R3.44 per passenger-trip at 100% stopping. This form of infrastructure is followed by the queue-bypass lane and the dedicated taxi lane both with a sensitivity of 47%. The queue-jumping lane and the single lane pre-signal strategy are not affected by this variable as the only passengers that board or alight the taxi takes place during the red traffic cycle. This has the significant advantage of keeping the user cost down but the drawback of only being able to allow a small number of transfers over each traffic cycle.

The total cost per passenger per one-way trip with the increase in minibus taxi vehicle-hours travelled in a month is illustrated in Figure 4-17.

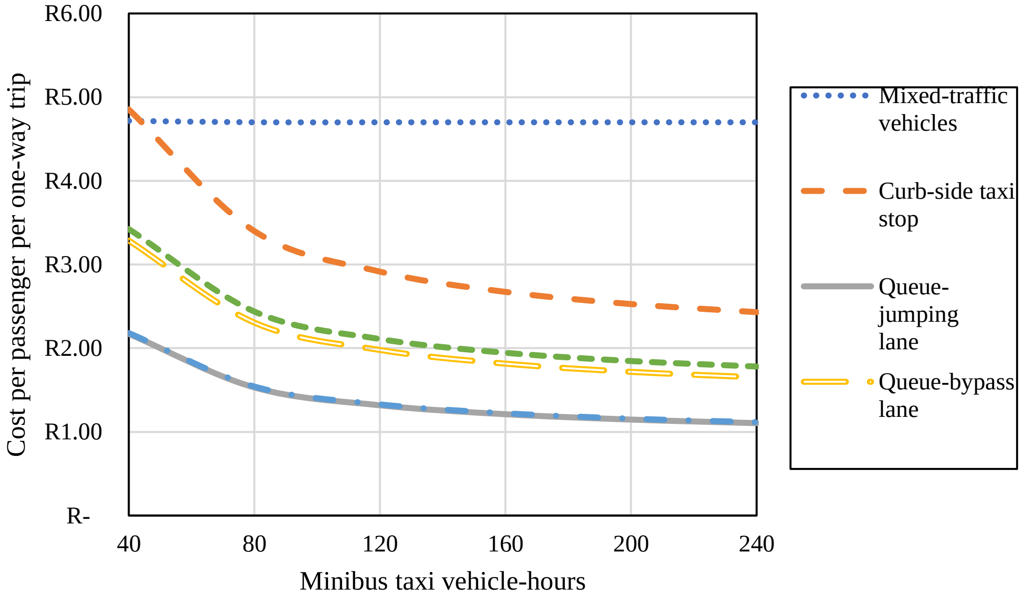


Figure 4-17: Cost per passenger per one-way trip with the increase in minibus taxi vehicle-hours

The number of minibus taxi vehicle-hours travelled in a month has no effect on the hourly cost of mixed-vehicle traffic and therefor a sensitivity of 0% is observed. Regarding the minibus taxi cost per passenger-trip, the most significant sensitivity was observed with the minibus taxi vehicle-hours variable: the dedicated taxi lane had a sensitivity of 104%, followed by the queue-jumping lane and single lane pre-signal strategy that had a sensitivity of 109% and 107% respectively. The greatest sensitivity was attributed to the curb-side taxi stop and queue-bypass lane with a sensitivity of 112% and 111%.

All the infrastructure forms had a significantly lower cost per passenger-trip compared to the passenger trip cost of private vehicle users which amounted to R4.70 per trip. It was observed that with the increase in vehicle-hours travelled by minibus taxis in a month, the cost reduces exponentially, and tends to reach an upped bound in hours travelled after which the benefits would not be that significant to minibus taxi operators. Between 40 and 80 hours the most significant reduction in cost is observed with an average of R0.94 reduction in cost across the infrastructure forms. At 200 hours, the curve tends to flatten which can be assumed to be the monthly hours spent driving from which taxi drivers would benefit the most.

Finally, a model was generated using the most optimal variables from each sensitivity analysis. These values do not necessarily result in the lowest cost outcomes but are the most realistic values that can be expected in conjunction with keeping the cost low. Table 4-7 summarises the variables and values used, and Figure 4-18 illustrates these results.

Table 4-7: Variables and values used in final model

Variable	Value used
Length of corridor	5 km
Ratio of minibus taxi occupancy to private vehicle occupancy	16:2
Passenger handling time for minibus taxis	8 seconds
Percentage of minibus taxis stopping	60%
Minibus taxi vehicle-hours	200

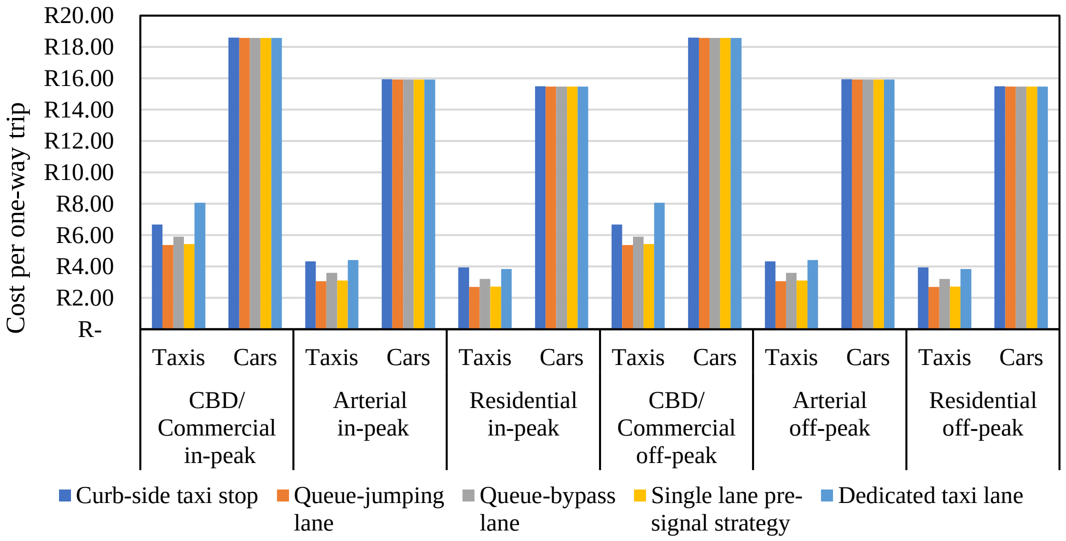


Figure 4-18: Total cost per passenger per one-way trip

Despite travelling 4 kilometres more than in the base model, the cost per passenger-trip for minibus taxis remain relatively low: in the case of the CBD/Commercial location, the cost varies between R5.38 for the queue-jumping lane and R8.07 for the dedicated taxi lane. The private vehicle cost per passenger-trip, however, is significantly higher at R18.60 per trip.

Chapter 5 investigates taxi driver behaviour that was recorded using a drone over various locations in Pretoria.

5 EMPIRICAL 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 more passengers they can transport in a day, the higher income they earn and thus it is often in their best interest to weave their way through traffic to get ahead of the congestion.

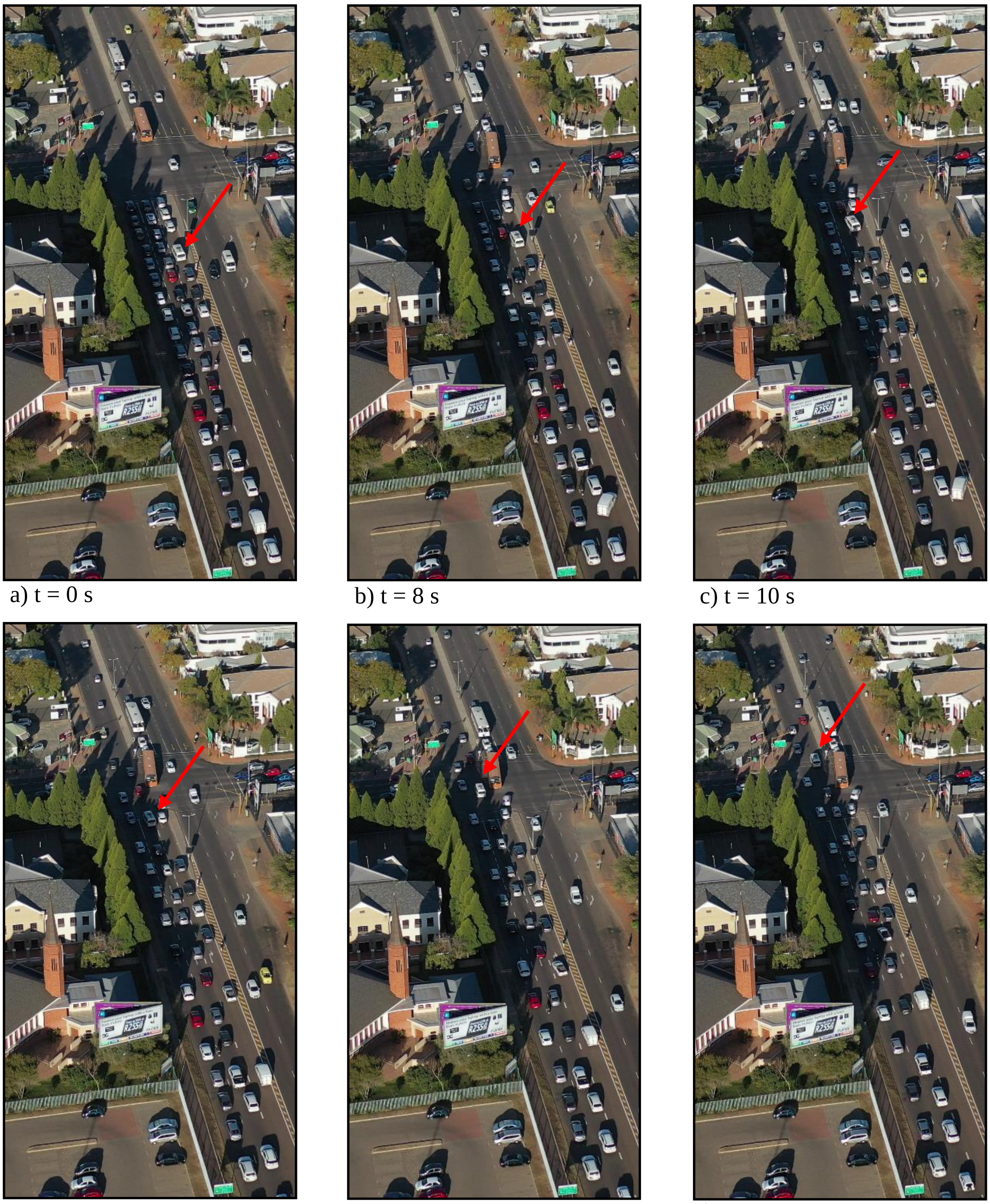
With the use of unmanned aerial vehicles, commonly referred to as “drones”, the behaviour of the minibus taxis was observed. Drones have undergone significant developments and advancements during the last few years. This technology has become accessible to the general public in the research environment. They allow for improved surveillance whilst minimising safety and security risks. Video footage obtained from drones can provide the researcher with high fidelity data and at the same time minimise the time spent monitoring the traffic scenarios as only a single operator is required. For this project a low-cost, commercially available drone was utilised to monitor typical traffic scenarios and interactions between minibus taxis and mixed-vehicle traffic along various corridors in the Pretoria area.

5.1 CASES OF MINIBUS TAXIS OBSERVED

As illustrated in Case 1, 2, and 3, the delay advantage that the operators try to gain at an intersection often corresponds to the models investigated in this study.

5.1.1 Case 1

In Figure 5-1 a minibus taxi was 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 8 vehicles in the queue. The behaviour displayed in the first case is similar to the queue-jumping lane model and jumping past such a long queue of vehicles saves this particular taxi approximately 24 seconds.



a) t = 0 s
b) t = 8 s
c) t = 10 s
d) t = 11 s
e) t = 14 s
f) t = 16 s

Figure 5-1: Minibus taxi creating own informal priority, Case 1

5.1.2 Case 2

The second case, as Figure 5-2 illustrates, is similar to the first in that the operation of an informal queue-jumping lane was observed. This time, however, two minibus taxis skip the queue as soon as the traffic signal turns green. From their behaviour it is clear that the taxi travelling behind attempted to push in first after which allowing the taxi in front of it to do the same. This illustrates the sense of community minibus taxi operators have, knowing the struggles of their fellow operator, and attempting to help the other out when the opportunity arises. In this case, the two taxis skipped a queue of over 12 vehicles and were able to save an approximate 66 seconds. This is due to the traffic light turning red before the entire queue could dissipate. This demonstrates why, during peak traffic, transit priority infrastructure could be of such value to minibus taxi operators and passengers.

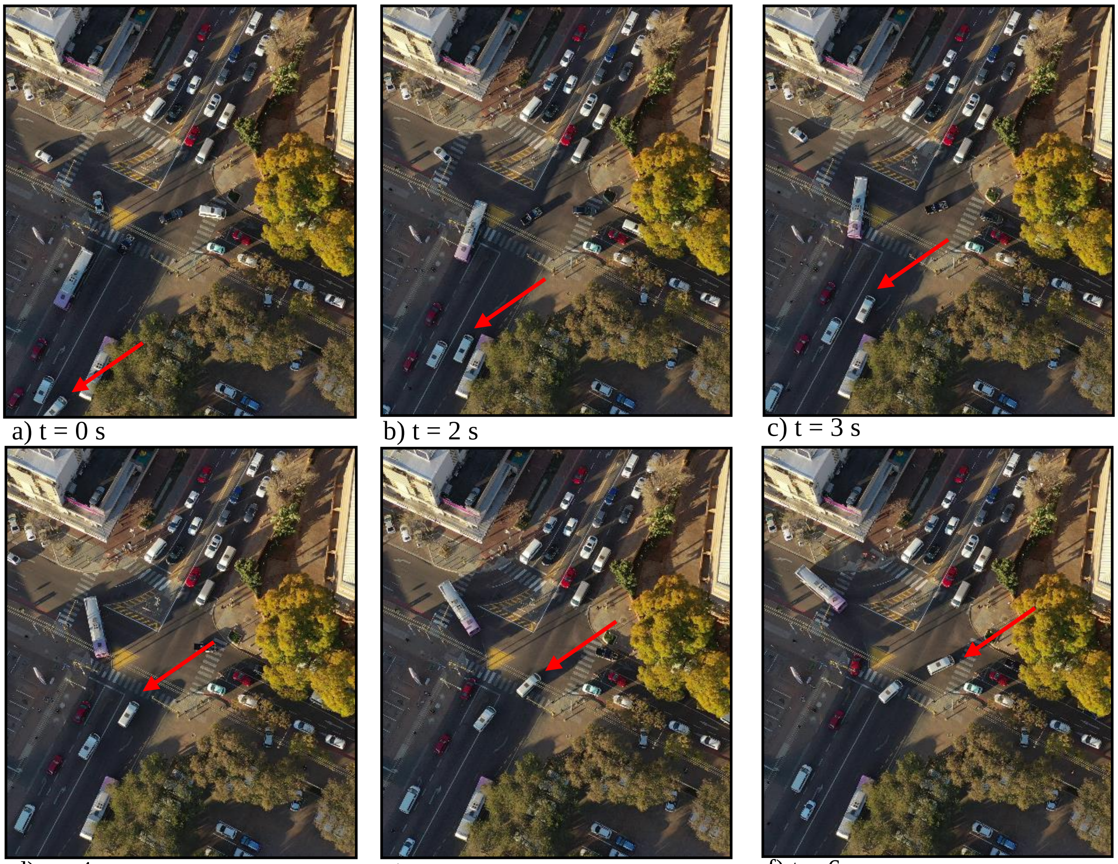
a) t = 0 s b) t = 4 s c) t = 6 s

d) t = 8 s e) t = 10 s f) t = 12 s

Figure 5-2: Minibus taxi creating own informal priority, Case 2

5.1.3 Case 3

In the final case that was observed, as illustrated in Figure 5-3, a minibus taxi is seen travelling in the lane of the oncoming traffic after which it makes a right turn. In contrast with the previous two cases, this behaviour is quite dangerous and even though operating according to the single lane pre-signal strategy, without the necessary traffic signalling, behaviour like this can result in a road accident. The time that was saved in this case is miniscule as the queue that formed at the intersection only amounted to the single vehicle travelling on front of it.



a) t = 0 s
b) t = 2 s
c) t = 3 s
d) t = 4 s
e) t = 5 s
f) t = 6 s

Figure 5-3: Minibus taxi creating own informal priority, Case 3

Figure 5-4 illustrates a minibus taxi travelling along a congested corridor. The time taken for this taxi operator to travel the short distance of 0.96 km was 5 minutes or at an average speed of 11.52 km/h. The first intersection does not require any form of transit priority but it is clear that the second one does. The second intersection observed in Figure 5-4 is the same intersection captured and analysed in Figures 5-1 and 5-2.

Depending on the finances available to the government, any of the forms of transit priority infrastructure investigated and modelled in this study would be suitable bar the single lane pre-signal strategy as this infrastructure form would not work in a double lane road.

a) t = 0 s

b) t = 268 s

Figure 5-4: Minibus taxi travelling on a congested corridor

5.2 THE NEED FOR PARATRANSIT INFRASTRUCTURE

It was observed, throughout the course of this study, that there is a distinct shortage of infrastructure for minibus taxi operators pertaining to boarding and alighting of passengers. Due to the dynamic, demand-responsive nature of the minibus taxi industry, drivers are often required to make informal stops at locations popular to pedestrians as indicated in Figure 5-5. The informal stops cause congestion on often busy roads and have, in some cases, lead to accidents.

a) t = 0 s

b) t = 2 s

c) t = 4 s

d) t = 7 s

Figure 5-5: Informal stop by a minibus taxi

The onus rests on the shoulders of government, national, provincial, and local, to observe and respect legislation that has been passed recognising the importance of the minibus taxi industry and, by extension support the industry through providing implicit subsidies to the industry in the form of these four transit infrastructure forms. The construction of these transit forms of infrastructure would be equivalent to giving minibus taxi operators cash in hand each month. The economic benefit of time savings would ensure that the cost to construct the infrastructure would not be a lasting liability.

Providing minibus taxis with the advantage of reduced delay not only saves the operator money due to reduced wear and tear on the vehicles, it also saves the driver time allowing more trips to be made and thus increasing the income. In addition to this, and perhaps most importantly, it saves time for the passengers, often travelling very long distances, spending numerous hours on the road each week due to living far from work as a result of spatial injustices of the past.

Improving the operating conditions of the minibus taxi industry would reduce the friction between government officials and minibus operators and owners. The extending of the olive branch could be viewed by the taxi industry as a government that finally cares about the backbone of the public transport industry and this might lead to the industry working with the local and provincial government in their efforts to implement an integrated public transport network

6 CONCLUSIONS AND RECOMMENDATIONS

This study consisted of identifying priority infrastructure alternatives from literature and to determine their suitability for improving operating conditions in the paratransit industry; developing mathematical models to ascertain the suitability of the various priority infrastructure measures under a range of operating and demand conditions; and quantifying the high-level economic impact that the selected priority infrastructure would have on paratransit operators, their passengers, other road users, and society at large. The conclusions and recommendations are presented, addressing each of the objectives outlined in Section 1.2.

6.1 CONCLUSIONS

6.1.1 Priority Infrastructure Alternatives

Four forms of transit infrastructure were identified, namely, the queue-jumping lane, queue-bypass lane, single lane pre-signal strategy, and the dedicated taxi lane which were compared to the operating conditions of the curb-side taxi stop.

6.1.2 Mathematical Model Development

The development of the model consisted of five basic steps which included the formulation of the problem statement with the aid of literature research which led to the preparation of the objectives and deliverables that were expected from the model. The model building process consisted of the four main components that were considered to be the most significant in simulating the real-world scenario of the traffic situation and interaction between public transport and ordinary traffic which consisted of designing a signalised intersection, considering the user cost of both minibus taxis as private vehicles, quantifying the operating cost of the vehicles considered in the modelled scenario and determining the capital cost required to construct the various infrastructure forms. Calibration of the model followed by conducting traffic counts to determine the most accurate results from the model and a sensitivity analysis was conducted pertaining to the variables in the model around which there was the most uncertainty.

6.1.3 Economic Impact of Priority Infrastructure

The outputs delivered by the model included travel time, user cost per hour, operating cost per hour, fuel cost per one-way trip, carbon dioxide emissions per one-way trip, total construction cost, and total cost per hour. The results of the outputs are summarised as follows:

- When compared to the curb-side taxi stop, the queue-jumping lane and single lane pre-signal strategy both show the greatest reduction in travel time with a 56% decrease equating to a 3.2-minute reduction in travel time. The queue-bypass lane and the dedicated taxi lane reduced travel time by 33% or 1.8 minutes along the corridor.
- All four forms of infrastructure, when compared to the curb-side taxi stop, show a reduction in user cost varying between 41% and 72%.
- When the user cost is reduced to a cost per passenger per trip, the user cost per minibus taxi passenger in most cases is lower than that of a private vehicle passenger.
- The maximum number of passengers that can board or alight a taxi in an hour is 1674 for the curb-side tai stop, queue-bypass lane, and the dedicated taxi lane. For the queue-jumping lane and single lane pre-signal strategy these values are 28 and 33 respectively.
- The operating cost decreases by 51% when the curb-side taxi stop is compared to the queue-jumping lane and 50% when compared to the single lane pre-signal strategy. All other forms also demonstrate a decrease in cost.
- The percentage in operating cost a minibus taxi operator can save when the curb-side taxi stop is compared to the other forms of transit infrastructure, ranges between 28% and 48%.
- The monthly savings a minibus taxi operator can incur when the curb-side taxi stop is compared to the other infrastructure forms, is over R32 000 in the case of the queue-jumping lane and single lane pre-signal strategy or over R12 000 for the queue-bypass lane and dedicated taxi lane.
- The fuel cost and carbon emissions emitted when travelling along the corridor decreases along all four forms of infrastructure. The private vehicle fuel cost and emissions produced is lower than that of the minibus taxis but when passengers are taken into account, the costs and emissions per minibus taxi passenger is between 29% and 57% lower than a private vehicle passenger.
- The dedicated taxi lane showed the greatest capital cost and the queue-jumping lane the lowest. Capital cost does not, however, have the greatest effect on the holistic cost of the infrastructure and the dedicated taxi lane could be advantageous in some cases.
- When the total cost per passenger-trip is considered in the CBD/Commercial location, the cost per trip ranges between R1.04 for the single lane pre-signal strategy, and R2.27 for the curb-side taxi stop. The cost for a passenger-trip in a private vehicle is R4.72.
- The single lane pre-signal strategy is the transit infrastructure form that allows the greatest number of passengers to be transported by minibus taxi. This is followed by the queue-

jumping lane. The curb-side taxi stop, queue-bypass lane, and the dedicated taxi lane all three have the lowest passenger capacity.

The impacts of the of varying certain variables in the models between a lower and upper bound were measured. 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 number of vehicle hours a minibus taxi operator spends on the road in a month. The results of the sensitivity analysis are summarised as follows:

- The total private vehicle cost per passenger shows the greatest increase in cost, ranging between R4.10 for a 1-kilometre trip to R41.26 for a 9-kilometre trip. Conversely, the queue-jumping lane incurs the lowers cost per passenger trip, ranging between R0.53 to R8.99. The dedicated taxi lane is the transit priority infrastructure with the most expensive total cost per passenger increasing from R1.09 to R15.43 for a 9-kilometre trip.
- With the change in ratio of minibus taxi passengers to private vehicle passengers, private vehicles displayed a 75% sensitivity. The curb-side taxi stop was the most sensitive form of infrastructure with 80%. The cost per passenger when a private vehicle is full amounts to R2.26 per 1-kilometre trip whereas, in the case of the curb-side taxi stop, a minibus taxi filled to capacity costs R2.38 per passenger trip.
- Passenger handling time has no effect on private vehicles and therefore a 0% sensitivity was observed. The curb-side taxi stop had a 65% sensitivity which was the highest. At a handling time of 25 seconds the cost per passenger-trip for minibus taxis using the curb-side taxi stop equals the cost per passenger trip for private vehicles. The other infrastructure forms are all still significantly lower in cost at that value.
- The percentage of minibus taxis stopping also has no effect on the hourly cost of private vehicles. The curb-side taxi stop is the most sensitive to the percentage of minibus taxis stopping with a sensitivity of 69% or increasing from R1.08 per passenger-trip at 0% taxis stopping to R3.44 per passenger-trip at 100% stopping.
- When varying the minibus taxi vehicle-hours, the greatest sensitivity is attributed to the curb-side taxi stop and queue-bypass lane with a sensitivity of 112% and 111%.
- Generating a final model with a corridor length of 5 kilometres, a ratio of minibus taxi occupancy to private vehicle occupancy of 16:2, a passenger handling time of 8 seconds, the percentage of minibus taxis stopping to pick up or drop off passengers of 60%, and 200 minibus-taxi vehicle hours travelled monthly, results in a passenger-trip cost between

R5.38 for the queue-jumping lane and R8.07 for the dedicated taxi lane. The private vehicle cost per passenger-trip, however, is significantly higher at R18.60 per trip.

A low-cost, commercially available drone was used to monitor traffic behaviour, particularly that of the minibus taxis and it was observed that the drivers often try to cut corners and skip traffic to save time during peak traffic scenarios. In two cases driving patterns similar to the case modelled for the queue-jumping lane were displayed cutting time off the drivers' trip by up to 66 seconds. It was also observed that there is a shortage of infrastructure for minibus taxi operators to pick up and drop off passengers often resulting in them making informal stops that cause congestion.

The implementation of the transport priority infrastructure forms in conjunction with already existing public transport networks, like that of the BRT, would be quite unfeasible. Two public transport networks running next to each other would be superfluous and operating both transportation modes on the same line would increase the delays experienced by the BRT vehicles. Where the minibus taxis are needed, however, is in regions where the BRT systems do not yet reach: using the minibus taxis as feeder systems to the BRT and constructing the priority infrastructure forms on the busy minibus taxi corridors could be the genesis of a public transport network that works for everyone.

6.2 RECOMMENDATIONS

Based on the results derived from the development of the transit priority models and having found that each of them presents significant benefits to the minibus taxi industry, it is necessary to simulate the traffic scenarios at a microscopic scale, demonstrating the interactions between the minibus taxis and private vehicles more accurately.

Having identified a corridor where a form of transit priority infrastructure can be implemented and the intersection to which it will add the most value, it presents the opportunity to develop a model that can identify potential locations for the implementation of these forms of infrastructure across a larger network.

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APPENDIX A

Table A-1: Travel time

		Travel time				
		Curb-side taxi stop	Queue-jumping lane	Queue-bypass lane	Single lane pre-signal strategy	Dedicated taxi lane
CBD/ Commercial in-peak	Taxis	5.7	2.5	3.8	2.5	3.8
	Cars	2.6	2.6	2.6	2.6	2.6
Arterial in-peak	Taxis	4.5	1.3	2.6	1.3	2.6
	Cars	1.4	1.4	1.4	1.4	1.4
Residential in-peak	Taxis	4.3	1.1	2.4	1.1	2.4
	Cars	1.2	1.2	1.2	1.2	1.2
CBD/Commercial off-peak	Taxis	5.7	2.5	3.8	2.5	3.8
	Cars	2.6	2.6	2.6	2.6	2.6
Arterial off-peak	Taxis	4.5	1.3	2.6	1.3	2.6
	Cars	1.4	1.4	1.4	1.4	1.4
Residential off-peak	Taxis	4.3	1.1	2.4	1.1	2.4
	Cars	1.2	1.2	1.2	1.2	1.2

Table A-2: User cost per hour

		User Cost Per Hour				
		Curb-side taxi stop	**Queue-jumping lane**	**Queue-bypass lane**	**Single lane pre-signal strategy**	**Dedicated taxi lane**
CBD/ Commercial in-peak	Taxis	R5 517.52	R2 664.29	R3 722.78	R2 716.25	R3 741.29
	Cars	R1 185.02	R1 167.94	R1 167.94	R1 167.94	R1 167.94
Arterial in-peak	Taxis	R1 288.86	R405.92	R757.06	R412.58	R762.53
	Cars	R1 100.09	R1 071.05	R1 071.05	R1 071.05	R1 071.05
Residential in-peak	Taxis	R2 436.56	R692.10	R1 384.09	R705.88	R1 394.92
	Cars	R392.51	R380.49	R380.49	R380.49	R380.49
CBD/ Commercial off-peak	Taxis	R1 880.09	R924.70	R1 268.54	R946.31	R1 274.84
	Cars	R488.80	R481.75	R481.75	R481.75	R481.75
Arterial off-peak	Taxis	R497.34	R158.74	R292.13	R161.80	R294.24
	Cars	R659.48	R642.07	R642.07	R642.07	R642.07
Residential off-peak	Taxis	R767.52	R221.09	R435.99	R226.15	R439.40
	Cars	R186.20	R180.49	R180.49	R180.49	R180.49

Table A-3: User cost per passenger per trip

		User cost per passenger per trip				
		Curb-side taxi stop	Queue-jumping lane	Queue-bypass lane	Single lane pre-signal strategy	Dedicated taxi lane
CBD/ Commercial in-peak	Taxis	R8.92	R0.73	R1.11	R0.73	R1.12
	Cars	R1.17	R1.15	R1.15	R1.15	R1.15
Arterial in-peak	Taxis	R1.30	R0.38	R0.76	R0.38	R0.77
	Cars	R0.64	R0.62	R0.62	R0.62	R0.62
Residential in-peak	Taxis	R1.24	R0.32	R0.71	R0.32	R0.71
	Cars	R0.55	R0.53	R0.53	R0.53	R0.53
CBD/ Commercial off-peak	Taxis	R1.65	R0.73	R1.11	R0.73	R1.12
	Cars	R1.17	R1.15	R1.15	R1.15	R1.15
Arterial off-peak	Taxis	R1.30	R0.38	R0.76	R0.38	R0.77
	Cars	R0.64	R0.62	R0.62	R0.62	R0.62
Residential off-peak	Taxis	R1.24	R0.32	R0.71	R0.32	R0.71
	Cars	R0.55	R0.53	R0.53	R0.53	R0.53

Table A-4: Operating cost per hour

		Operating cost per hour				
		Curb-side taxi stop	Queue-jumping lane	Queue-bypass lane	Single lane pre-signal strategy	Dedicated taxi lane
CBD/ Commercial in-peak	Taxis	R1 966.60	R1 118.79	R1 412.43	R1 140.72	R1 416.75
	Cars	R3 600.14	R3 600.14	R3 600.14	R3 600.14	R3 600.14
Arterial in-peak	Taxis	R502.06	R240.52	R337.85	R244.70	R339.12
	Cars	R6 131.35	R6 131.35	R6 131.35	R6 131.35	R6 131.35
Residential in-peak	Taxis	R966.98	R455.29	R642.00	R464.85	R644.53
	Cars	R2 541.15	R2 541.15	R2 541.15	R2 541.15	R2 541.15
CBD/ Commercial off-peak	Taxis	R670.12	R387.91	R481.29	R397.01	R482.76
	Cars	R1 484.98	R1 484.98	R1 484.98	R1 484.98	R1 484.98
Arterial off-peak	Taxis	R193.73	R93.99	R130.37	R95.89	R130.86
	Cars	R3 675.61	R3 675.61	R3 675.61	R3 675.61	R3 675.61
Residential off-peak	Taxis	R304.60	R145.28	R202.23	R148.75	R203.03
	Cars	R1 205.44	R1 205.44	R1 205.44	R1 205.44	R1 205.44

Table A-5: Fuel cost per one-way trip

	Fuel cost per one-way trip				
	Curb-side taxi stop	Queue-jumping lane	Queue-bypass lane	Single lane pre-signal strategy	Dedicated taxi lane
Taxis	R3.22	R2.00	R2.49	R1.99	R2.49
Cars	R1.18	R1.18	R1.18	R1.18	R1.18

Table A-6: Emissions per trip

	Emissions per trip				
	Curb-side taxi stop	Queue-jumping lane	Queue-bypass lane	Single lane pre-signal strategy	Dedicated taxi lane
Taxis	0.4725	0.2929	0.3654	0.2926	0.3654
Cars	0.1737	0.1737	0.1737	0.1737	0.1737

Table A-7: Total infrastructure cost

Total infrastructure cost				
Curb-side taxi stop	Queue-jumping lane	Queue-bypass lane	Single lane pre-signal strategy	Dedicated taxi lane
R400 000.00	R34 212.50	R130 525.00	R400 000.00	R1 550 000.00

Table A-8: Cost per one-way trip

		Cost per one-way trip				
		Curb-side taxi stop	Queue-jumping lane	Queue-bypass lane	Single lane pre-signal strategy	Dedicated taxi lane
CBD/ Commercial in-peak	Taxis	R2.27	R18.60	R27.78	R18.80	R30.08
	Cars	R4.72	R7.05	R7.05	R7.05	R7.05
Arterial in-peak	Taxis	R32.97	R10.80	R19.96	R10.91	R21.16
	Cars	R6.28	R6.25	R6.25	R6.25	R6.25
Residential in-peak	Taxis	R31.66	R9.53	R18.66	R9.61	R19.70
	Cars	R6.14	R6.12	R6.12	R6.12	R6.12
CBD/ Commercial off-peak	Taxis	R40.84	R18.59	R27.77	R18.80	R30.08
	Cars	R7.07	R7.05	R7.05	R7.05	R7.05
Arterial off-peak	Taxis	R32.97	R10.81	R19.96	R10.91	R21.16
	Cars	R6.28	R6.25	R6.25	R6.25	R6.25
Residential off-peak	Taxis	R31.66	R9.52	R18.66	R9.61	R19.70
	Cars	R6.14	R6.12	R6.12	R6.12	R6.12

Table A-9: Cost per one-way trip per passenger

		Cost per one-way trip per passenger				
		Curb-side taxi stop	Queue-jumping lane	Queue-bypass lane	Single lane pre-signal strategy	Dedicated taxi lane
CBD/ Commercial in-peak	Taxis	R2.27	R1.03	R1.54	R1.04	R1.67
	Cars	R4.72	R4.70	R4.70	R4.70	R4.70
Arterial in-peak	Taxis	R1.83	R0.60	R1.11	R0.61	R1.18
	Cars	R4.19	R4.17	R4.17	R4.17	R4.17
Residential in-peak	Taxis	R1.76	R0.53	R1.04	R0.53	R1.09
	Cars	R4.10	R4.08	R4.08	R4.08	R 4.08
CBD/ Commercial off-peak	Taxis	R2.27	R1.03	R 1.54	R1.04	R1.67
	Cars	R4.72	R4.70	R4.70	R4.70	R4.70
Arterial off-peak	Taxis	R1.83	R0.60	R1.11	R0.61	R1.18
	Cars	R4.19	R4.17	R4.17	R4.17	R4.17
Residential off-peak	Taxis	R1.76	R0.53	R1.04	R0.53	R1.09
	Cars	R4.10	R4.08	R4.08	R4.08	R4.08