A COMPARISON OF DIRECT AND TRUNK-FEEDER CONFIGURATIONS FOR BUS RAPID TRANSIT SYSTEMS

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DISSERTATION SUMMARY

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Bus Rapid Transit (BRT) systems have gained popularity worldwide as a cost-effective alternative to more expensive urban rail systems, carrying around an estimated 33 million passengers each weekday (https://brtdata.org/). In South Africa, several BRT systems are either in the planning stage, detailed design, or construction, with only a few being operational (Ackerman, 2015). When planning BRT operations, planners need to decide when to use feeder or direct routes to supplement the trunk routes: this takes into consideration that trunk routes cannot be built to be within walking distance of large catchments of people. This research aims to explore the strengths and weaknesses of two BRT-based network types: trunk-feeder (buses operating inside and outside the BRT trunk corridor are segregated and operate independently) and direct (buses operating outside the trunk corridor can enter and leave it, providing additional services in the corridor).

The Rea Vaya BRT system has both 'trunk-feeder' and 'direct' networks in operation and is used as a case study for this research. Rea Vaya routes have three classifications: trunk, complementary, and feeder routes. Trunk routes (T) use dedicated median-exclusive busways only. Complementary routes (C) use a combination of normal mixed traffic roads and dedicated median-exclusive busways. Feeder routes (F) start and end at Rea Vaya trunk stations using normal mixed traffic roads. The approach for the study is empirical and evidence based.

The activities of the research are to:

- develop a list of observable indicators to compare trunk-feeder and direct BRT networks;
- collect data on indicators for trunk, feeder, and complementary routes;

- analyse the data using different analytical tools; and
- make direct versus trunk-feeder network recommendations for BRT systems in South African cities.

Data collection is from four sources: station surveys, on-board surveys, ticketing information, and system data sourced from the operator. In this study, five key indicators (reliability, saturation, speed, load factor, & operating costs) are identified in guiding the comparative analysis. This led to the formulation of five hypotheses to be tested and make reasonable recommendations.

According to analytical studies, the case for a trunk-feeder network rests on economies of density where it is cheaper per passenger to operate larger trunk buses on the main streets with high demand. For Rea Vaya, it is cheaper per passenger to operate trunk and feeder routes compared to the complementary routes. This saving is because of using larger vehicles (18m articulated buses) on the trunk corridor to achieve more capacity and costs are spread over a larger passenger number. However, the costs are highest for the trunk routes because of increased cycle times (and long routes), and increased fleet size requirements. From a cost perspective, trunk routes work best for densely populated areas but not over long distances.

Literature suggests that the number of transfers that a trunk-feeder configuration require creates several operational inefficiencies and slower commercial speeds due to considerably higher dwell times (DTs). This is not entirely the case for Rea Vaya BRT system. While the trunk and feeder routes have longer dwell times than the complementary routes, the vehicle operating speeds for the trunk and feeder buses are higher than that of the complementary buses. The average vehicle operating speed for trunk buses is 30 km/h; for feeder buses, it is 25 km/h, and for complementary buses, it is 20 km/h. This is because the complementary buses are operated on major arterials with high levels of congestion before joining the trunk corridor. It can be concluded that the potential time savings of complementary routes through avoiding transfers does not materialise as it is more than offset by the slow vehicle speeds on mixed traffic routes.

Overall, the results indicate a mixed view with regards to direct and trunk-feeder BRT networks in a South African context. While direct networks have an advantage of avoiding transfers, they are also found to be competitive in terms of headway reliability, maintaining low dwell times at the stations and having a high load factor (during peak only and consistent with the high peak to base ratio observed in South Africa).

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LIST OF SYMBOLS

C_{BH} = Unit cost of one bus-hour of operation

C_{BK} = Unit cost of one bus-kilometre of operation

C_{FS} = Unit cost of keeping one bus available for operation for one year

K_h = Hourly available docking length (time space measurement) (metre-minutes)

K_L = Kerb length (space allocated for buses to stop at the station) (metre)

B = Hourly available space for a bus on the kerb length (bus-minutes)

B_L = Bus length (metre)

D_T = Total docking time per hour (bus-minutes)

N_B = Number of buses per hour

DT_{avg} = Average dwell time (minutes)

$Q_{T =}$ Total queueing time per hour (bus-minutes)

QT_{avg} = Average queueing time (minutes)

T_t = Total time spent at the station

S_t = The fraction of time that a specific bus type occupies the station

S_T = Total saturation level

S_{tT} = Saturation level for trunk buses

S_{tF} = Saturation level for feeder buses

S_{tC} = Saturation level for complementary buses

t = General index

S = Vehicle operating speed

D = Route distance from start to the end of the route

T = Travel time from start to the end of the route

Kb = Kilometres operated by the buses

Cp = Capacity, calculated by multiplying vehicle size by the frequency

ST = Passenger trip speed

TD = Trip distance

TT = Trip time

LF = Load factor

Pax km = Passenger-kilometres

P km = Place-kilometres

Irr = Irregularity index

V_{size} = Vehicle capacity

ACRONYMS AND ABBREVIATIONS

AFC	Automatic Fare Collection
BRT	Bus Rapid Transit
C	Complementary Route
CBD	Central Business District
CO_2	Carbon Dioxide
CV	Coefficient of Variation
DT	Dwell Time
EMV	Europay, Mastercard and Visa
F	Feeder Route
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GPS	Global Positioning System
GTFS	General Transit Feed Specification
IDP	Integrated Development Plan
ITDP	Institute for Transportation and Development Policy
IPTN	Integrated Public Transport Network
ITP	Integrated Transport Plan
KM	Kilometre
Km/h	Kilometre per Hour
No.	Number
NO_x	Nitrogen Oxide
O-D	Origin-Destination
PPHPD	Passengers Per Hour Per Direction
PRASA	Passenger Rail Agency of South Africa
PUTCO	Public Utility Transport Corporation
SIPTN	Strategic Integrated Public Transport Network
SLA	Service Level Agreement
SO_2	Sulphur Dioxide
SPTN	Strategic Public Transport Network
T	Trunk Route
TRNDP	Transit Route Network Design Problem
UATP	African Association of Public Transport
UIF	Unemployed Insurance Fund
UJ	University of Johannesburg
Vol	Volume

1. INTRODUCTION

According to the Institute for Transportation and Development Policy (ITDP), bus rapid transit (BRT) is a high-quality bus-based transit system that delivers fast, comfortable, and cost-effective services at metro-level capacities. This research aims to explore the strengths and weaknesses of two BRT-based network types: trunk-feeder (buses operating inside and outside the BRT trunk corridor are segregated and operate independently) and direct (buses operating outside the trunk corridor can enter and leave it, providing additional services in the corridor).

The approach taken is empirical and evidence-based, from passengers, operators, and owner's perspectives. The literature on bus system design suggests several advantages of direct over trunk-feeder networks, especially for medium-sized systems with lower passenger demand. However, theoretical and simulation studies usually make multiple assumptions and simplifications, ignoring real-world issues. There is limited literature on the comparative performance of these two networks in actual operations. This study aims to fill the gap by measuring and analysing their actual performance in the context of an operating BRT system with both networks. The aim will be to advance our understanding of the factors that drive the comparative performance of each type of network under real-world conditions and to provide some guidance for future planning and design (and adaptation) of BRT systems.

The City of Johannesburg's Rea Vaya BRT system has both 'trunk-feeder' and 'direct' networks in operation and is used as a case study for this research. Rea Vaya routes have three classifications: trunk, complementary, and feeder routes. Trunk routes (T) use dedicated median-exclusive busways only, with closed median stations that allow level boarding. Complementary routes (C) use a combination of normal mixed traffic roads and dedicated median-exclusive busways. Feeder routes (F) start and end at Rea Vaya trunk stations using normal mixed traffic roads, connecting passengers to trunk and complementary routes. In this study, the trunk-feeder network is represented by the trunk and feeder routes, and the direct network is represented by the complementary routes, offering a combination of in and out of trunk network operations.

The advantage of using Rea Vaya as a case study is that both networks are found in the same system, so any city-specific or system-specific differences that would usually occur (for example, urban form, demand, operating environment) when comparing across different cities and systems can be controlled. The main limitation of the case study approach is the potential inability to generalise the findings to systems beyond that which was studied. However, the method enables the collection of detailed data and the use of mixed-method analysis to extensively explore the issues that relate to the operation of trunk-feeder and direct BRT networks. It is thus considered a suitable methodology for this research. Data collection is from four sources: station surveys, on-board surveys, ticketing information, and system data sourced from the operator. A set of indicators is developed to compare trunk-feeder and direct BRT networks, and these include headway reliability, station saturation, average speed, load factor, and operating costs. A conclusion and further recommendations are also made concerning the BRT networks.

1.1. BACKGROUND

The optimal spatial arrangement of transit lines in an urban setting comprises four basic strategic competing networks structures: direct, trunk-feeder, exclusive and shared. The different possible network structures are represented in Figure 1.1, in a simple network diagram with Points A, B and C serving as origins and Point D as a destination. With direct lines, each passenger has a line that connects their origin and destination, passing through the subcentre (Point C), with no transfers required. Trunk-feeder allows all the passengers from the periphery to take a feeder mode to the subcentre (Point C), where a transfer is required to board a trunk bus to their destination. Exclusive lines have no intermediate stops, as each passenger has a line that connects to their origin and destination without stopping at in-between nodes, which means that each line is used only by passengers of a single Origin-Destination (O-D) pair. Shared lines are like exclusive lines but have a stop at the subcentre (Point C), presenting passengers whose trips start at Point C with more options of getting to their destination (Point D).

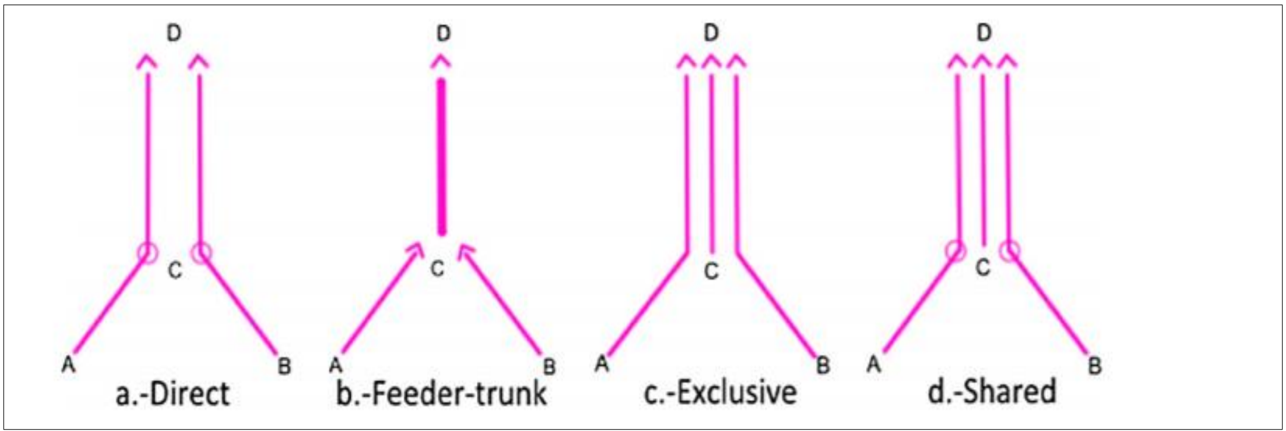

Figure 1:1 Graphical representation of the four-line structures
(Source: Gschwender et al., 2016)

According to Jara-Díaz et al. (2012), the three elements of an optimal public transport network are line structure, frequencies, and vehicle size. However, designing an optimal public transport system in an urban context is complex and continually evolving, making it hard to find the optimal

line structure for urban areas (Gshwender et al., 2016). It is not always easy to determine which one is better under different urban circumstances and with different demand structures.
Ferro and Behrens (2015) state that many public transport improvement initiatives involve restructuring the existing system. When implementing BRT system plans, the initiatives include a complete restructuring of paratransit direct models into trunk-feeder models to formalise the system. However, the move from direct to trunk-feeder networks has implications for the travel patterns in an urban territory. Also, some of the valuable characteristics of paratransit are overlooked. These include:

- paratransit services can be of use in peripheral areas due to their flexibility and demand responsiveness; and
- a complementary relationship between the trunk-feeder model and the existing paratransit sector can increase the coverage of the public transport system.

Most current public transport restructuring initiatives overlook these value characteristics (Salazar Ferro et al., 2012). Formal trunk-feeder public transport systems are more rigid than the paratransit-based model they are meant to replace (Ferro & Behrens, 2015). Cities in the global South[1] have been growing, specifically those located on the periphery, requiring a flexible and demand-responsive public transport system. Complementarity as an element of integration is required between trunk-feeder and direct paratransit models to provide a public transport system that is equitable, sustainable, and inclusive. In Southeast Asian cities, Cervero (2013) observed that successful complementarity between formal and paratransit modes is possible. Due to the poor state of roads (narrow roads and faulty pavements), paratransit services could flourish as they operate with small vehicles. These services were able to complement the existing high-capacity modes with relative success and acceptability by inhabitants.

The BRT trunk-feeder distributor model is an appropriate solution in certain contexts, but it is not the only solution. In South Africa, specifically, the current economic climate has resulted in enormous pressure on government fiscus. Subsequently, the government does not have enough funding for new infrastructure projects, which has prompted the need to determine if infrastructure-heavy projects are required, given South Africa's conditions. The move towards direct BRT networks could support lighter, less costly network while still providing a public transport system that is fit for purpose. The Rea Vaya BRT in Johannesburg is used as a case study to address the differences between a trunk-feeder versus a direct BRT network. The Rea Vaya BRT system was planned as the backbone of a future transport system in the City of

[1] Global South refers to regions of Latin America, Asia, Africa, and Oceania.

Johannesburg, integrated with rail services to provide high levels of accessibility, capacity, and mobility. Other prominent features of the Rea Vaya system are:

- exclusive, dedicated right-of-way bus lanes enabling trunk routes to operate separately from other traffic;
- high capacity (130 passengers per bus) 18m articulated vehicles for trunk routes and standard 12m buses for complementary and feeder routes;
- high floor vehicles requiring elevated station platforms to ensure level boarding, and standard buses with low floor door access on the left-hand side and high floor on the right-hand side of each bus;
- pre-boarding fare collection and verification at trunk stations and on-board systems for feeder and complementary routes in mixed traffic;
- a centralised bus operation centre; and,
- clear route maps, signage and real-time information displays visibly placed in stations and vehicles.

Rea Vaya commenced in 2009, starting with Phase 1A that included a trunk route operating between Ellis Park in Doornfontein and Thokoza Park in Soweto, linking with several feeder routes in Soweto. The Phase 1A trunk route has a length of 25 km and 27 stations. It was complemented by five feeder routes totalling 54 km and four complementary routes totalling 90 km. Phase 1B of Rea Vaya services commenced in October 2013, extending the trunk route from Noordgesig Extension in Soweto to the Auckland Park, Milpark, Parktown areas. The Phase 1B trunk route has a length of 18 km. It is complemented by 12 feeder routes totalling 62 km and six complementary routes totalling 82 km.

1.2. PROBLEM STATEMENT

The City of Johannesburg Rea Vaya has both types of networks (trunk-feeder and direct) in operation. These networks consist of trunk and feeder routes as well as complementary routes. When planning BRT operations, planners need to decide when to use feeder or direct routes to supplement the trunk routes, considering that trunk routes cannot be built within walking distance of large catchments of people. A considerable amount of literature has been written about trunk-feeder and direct BRT networks. According to Del Mistro (2012), the choice between trunk-feeder and direct network depends upon the corridor's physical characteristics, the ridership profile, the demographics of the current and potential ridership, the performance and purchase price of the available vehicles, the local operator's maintenance and labour costs, the ability to maintain reliable service schedules, availability of shelters, and various other factors. On the other hand, ITDP lists travel time, operational efficiencies, infrastructure, vehicle types, capacity, system image and customer friendliness as a basis to the comparison.

What is not always clear to planners is when to provide feeder or complementary routes and what criteria to use when making these decisions. According to Proboste et al. (2020), BRT has gained popularity in medium-sized cities as a means of mass transit. However, due to the size of the cities, no more than one massive transport corridor is usually required. These cities are faced with the decision on how to structure their services. Trip length, demand patterns, road network infrastructure, and intermodality are different in large and medium-sized cities.

While passenger demand, fare revenue and operating costs are critical criteria, other considerations are often overlooked, including system design and operational criteria. Importantly, it appears that a 'one size fits all' approach is not appropriate, and planners need to consider the cases more carefully for trunk-feeder versus direct networks in the context of the urban environment. Also, the relatively high capital and operating costs of the full specification BRT are prohibitive for many local authorities (Chitauka & Vanderschuren, 2014). With South Africa going through an economic crisis and low gross domestic product (GDP) growth rates, it has become increasingly challenging to make infrastructure investments. Systematic guidance is therefore needed to assist in determining the circumstances under which a trunk-feeder or direct network is most appropriate.

1.3. OBJECTIVE OF THE STUDY

The objective of this research is to determine the indicators that need to be considered in deciding whether to implement a trunk-feeder or a direct BRT network and to examine the performance of these two types of networks under similar operating environments. Ultimately, this can be used to give guidance to public transport planners about how to structure their services.

1.4. SCOPE OF THE STUDY

This research compares trunk-feeder and direct BRT networks only, using the Rea Vaya BRT system in the City of Johannesburg as a case study. Five Rea Vaya stations were surveyed for 12 hours. The stations were chosen strategically based on their locations along the BRT corridor and station characteristics. In terms of location, they provide a snapshot of operations at various critical points in the network, especially at stations where trunk, feeder and complementary routes converge. No longitudinal GPS data of vehicle movements is available over longer periods, so the study depends on manual observations over a short period. On-board surveys were conducted for three weeks on all 21 routes. The City of Johannesburg provided a complete set of passenger ticketing data for September 2017 for Phases 1A and 1B. The ticketing data is supplemented by route data, consisting of all the serviced routes, schedules and station and stop locations. Data on operating costs (including maintenance costs and insurance, for example) is sourced from the bus operator.

The research focuses on the perspectives of the passenger, operator, and owner (in this case, the City of Johannesburg) to answer the question of trunk-feeder versus direct BRT networks. The approach is purely empirical and evidence-based while focusing on the operational performance of BRT systems.

The following are excluded from the study:

- initial infrastructure costs;
- customer satisfaction surveys;
- an assessment of wider social and environmental impacts, for example accessibility, user fares, emissions, safety;
- case studies of other BRT systems (although literature from other BRT systems was used); and
- data relating to cash transactions.

1.5. METHODOLOGY

The activities of the research are to:

- develop a list of observable indicators to compare trunk-feeder and direct BRT networks;
- collect data on indicators for trunk, feeder, and complementary routes in the Johannesburg Rea Vaya system;
- analyse the data using different analytical tools; and
- make direct versus trunk-feeder network recommendations for BRT systems in South African cities.

The key findings from previous analytical studies are used to structure the research questions and develop a list of indicators.

The five key indicators that are identified in guiding the comparative analysis are:

- reliability
- saturation levels

- speed
- Load factor
- operating costs

These indicators have led to the formulation of the five hypotheses below:

Hypothesis 1: Trunk-feeder BRT networks have more headway regularity than direct BRT networks.
Hypothesis 2: Trunk-feeder BRT networks have higher saturation levels at the station.
Hypothesis 3: Direct BRT networks lower overall travel times by avoiding transfers, compared to trunk-feeder BRT networks, resulting in higher speeds.
Hypothesis 4: Trunk-feeder BRT networks have a higher load factor than direct BRT networks.
Hypothesis 5: Trunk-feeder BRT networks have reduced operating costs compared to direct BRT networks.

1.6. ORGANISATION OF THE REPORT

The dissertation comprises the following chapters:

- Chapter 1 serves as an introduction to the research topic.
- Chapter 2 contains a technical introduction based on a detailed literature review.
- Chapter 3 describes the analysis framework.
- Chapter 4 motivates the research methodology adopted for the investigation.
- Chapter 5 contains the results and discussion.
- Chapter 6 contains the conclusion and recommendations of the study.
- List of references.

2. LITERATURE REVIEW

This chapter outlines the literature on BRT, including a detailed description, its application, and performance-based indicators. Direct and trunk-feeder BRT networks as well as the analytical and theoretical studies conducted for both networks are explained in this chapter. The chapter concludes with a summary of the significant findings from the analytical studies and research gaps that motivate this study.

2.1. A DESCRIPTION OF BUS RAPID TRANSIT (BRT)

BRT has been described as a semi-rigid system, more flexible than a metro-type rail system but more rigid than conventional buses (Vuchic, 2007). It is an infrastructure-heavy system compared to the typical paratransit system (Ferro & Behrens, 2015). BRT trunk corridors require a considerable amount of capital investment compared to paratransit-based networks and are relatively cheaper and easier to implement than rail-based modes (Ferro & Behrens, 2015). BRT systems have evolved worldwide in the last 30 years, motivated by greater efficiency and value for money than potential alternatives. Apart from the cities already implementing a BRT system, there are many cities worldwide considering BRT as a cost-effective solution, given the lower initial capital cost associated with comparable rail-based public transport (Merkert et al., 2017).

BRT is a rapid mass transit mode of public transport that combines the speed and dependability of a rail service through having access to dedicated infrastructure with the operating flexibility and the cost-effectiveness of a conventional bus service (Deng & Nelson, 2011). Compared to conventional bus transport, BRTs succeed in offering speed, reliability, comfort, and high-frequency services. BRT systems can achieve this due to the segregated infrastructure they offer (Merkert et al., 2017).

A BRT system is a high quality, customer-oriented transport system that delivers fast, comfortable, and low-cost urban mobility to public transport users. Levinson et al. (2003) described BRT as a flexible mode of mass rapid transit, with high levels of information technologies that integrate stations and vehicles. A full BRT is a bus system that has the following characteristics (Wright & Hook, 2007):

- metro-quality service;
- an integrated network of routes and corridors;
- closed, high-quality stations;
- pre-board fare collection/verification;
- frequent and rapid service;

- modern, clean vehicles; and
- marketing identity and superior customer service.

BRT systems have gained popularity worldwide as a cost-effective alternative to more expensive urban rail systems. According to Cervero (2013), more than 150 cities worldwide have implemented a BRT system, carrying around an estimated 33 million passengers each weekday (https://brtdata.org/). The main features of BRT are (Cervero, 2013):

- dedicated bus lanes that enable BRT buses to operate separately from other traffic;
- high passenger capacity vehicles;
- location of busways in the median of the roadway rather than in the kerb lane;
- stations that provide level access between the platform and the vehicle floor;
- pre-boarding fare collection and verification; and
- clear route maps, signage and real-time information displays visibly placed within stations and on vehicles.

The evaluation of BRT performance is important and timely as BRT systems have evolved from their early implementation in Lima (Peru) and Curitiba (Brazil) in the early 1970s to systems being built around the world in very different shapes and sizes (Merkert et al., 2017).

2.2. MOTIVATION FOR IMPLEMENTING BRT

Globally, the motivation for implementing BRT systems has broadened with time. In countries such as Ottawa and Curitiba, the main reason behind the implementation of BRT was because it provided a cheaper option compared to Light Rail Transit. Cities such as Mexico and Bangkok, on the other hand, used BRT to supplement their pre-existing rail systems. BRT has also served as a cornerstone for public transport, especially for countries that lacked a viable public transport network. On a global scale, BRT has already proved its capacity to transport high numbers of passengers and be implemented in short time frames at a relatively low capital cost (Velasquez et al., 2017). The implementation of BRT also attempts to solve the congestion problems caused by inefficient transport systems.

According to Carrigan et al. (2014), BRT systems can influence the quality of life, productivity, health, and safety of people living in cities. BRT provides a higher quality of service than traditional urban bus operations because of reduced travel and waiting times, increased service reliability and improved user experience. BRT can reduce travel time owing to design and operational characteristics, including exclusive bus lanes, pre-boarding fare collection, high frequencies, and signal prioritisation. According to Carrigan et al. (2014) and Herrera et al. (2016), high quality and performance are related to how BRT systems are designed. In essence, to have a fast service, the operating speed needs to increase; to reduce the waiting time, buses need to pass by more frequently and at regular time intervals; passenger capacity must increase to make the system more comfortable for a given demand and headways need to be as regular as possible for better reliability.

Many physical and operational elements can influence BRT performance, including traffic signal times and coordination, the distance between stations and the interface between buses and stations. Deng and Nelson (2013) provided evidence that overtaking lanes significantly impact peak ridership and frequency, while long station spacing has a significant positive impact on peak hour operating speed. Herrera et al. (2016) selected broader BRT design characteristics that can significantly affect the performance of a BRT corridor:

- closed versus open system;
- corridor type;
- station type;
- operations;
- vehicle technology;
- intersection type; and
- control systems.

BRT can also have positive environmental impacts because of reduced greenhouse emissions and the latest technologies, such as compressed natural gas. Natural gas significantly reduces carbon dioxide emissions. BRT can also provide positive public health benefits through the reduction of road fatalities. BRT strives to be a safe mode of transportation. Table 2.1 summarises the positive impacts of BRT.

Table 2.1 The impact of BRT on quality of life

(Source: Carrigan et al., 2014)

Impact	How does BRT achieve benefit?	Empirical evidence
Travel time savings	• Segregated busways separate BRT buses from mixed traffic	• Johannesburg BRT users save on average 13 minutes each way
GHG and local air pollutant emissions reductions	• Reduce vehicle kilometres travelled by shifting passengers to high-capacity BRT buses • Replace/scrap older, more polluting traditional vehicles • Introduce newer technology BRT buses • Better driver training leads to improved driving cycles that have lower fuel consumption and emissions	• In Bogotá, the implementation of Transmilenio, combined with new regulations on fuel quality, is estimated to save nearly 1 million CO_2 per year. Mexico City Metrobus Line 1 achieved significant reductions in carbon monoxide, benzene, and particulate matter (PM2.5) inside BRT buses, traditional buses, and minibuses
Reduced safety improvements – reductions in fatalities and crashes	• Improve pedestrian crossings • Reduce vehicle kilometres travelled by shifting passengers to high-capacity BRT buses • Reduces interaction with other vehicles by segregating buses from mixed traffic • BRT can change drivers' behaviour by reducing on-the-road competition and improving training	• Bogotá's Transmilenio has contributed to reductions in crashes and injuries in two of the system's main corridors. On average, BRTs in the Latin American context have contributed to more than 40% reduction in fatalities and injuries on the streets where they were implemented
Reduced exposure to air pollutants	• Cleaner vehicle technologies and fuels lower the concentration of ambient air pollution citywide or inside the BRT vehicles • Reduce time passengers are exposed to air pollution at	• After the implementation of Transmilenio, Bogotá reported a 43% decline in SO_2 emissions, 18% decline in NO_x and a 12% decline in particulate matter By reducing emissions of local air pollutants, especially of

Impact	How does BRT achieve benefit?	Empirical evidence
	stations or inside the bus by reducing travel times	particulate matter, Metrobus Line 1 in Mexico City estimates more than 6000 days of lost work, 12 new cases of chronic bronchitis, and three deaths per year, saving an estimated USD $3 million per year
Increased physical activity	• Spacing of BRT stations tends to require longer walking distances than all other motorised modes, except for Metro • Higher operation speeds increase passengers' willingness to walk to the stations	• Mexico City's Metrobus passengers walk an average of an additional 2.75 minutes per day than previously • Users of the Beijing BRT have added 8.5 minutes of daily walking because of the BRT system

According to the economic analysis on Phases 1A and 1B of Rea Vaya conducted in 2012, transit generally has a net positive impact of up to 10% on property values close to BRT stations (Standish et al., 2012). BRT has proven to be an effective and affordable transportation option for large-sized cities where it complements or substitutes rail-based systems, playing a key role in complex multimodal networks with several massive transport corridors (Proboste et al., 2020).

2.3. PERFORMANCE CHARACTERISTICS OF BRT

BRT system performance can vary significantly, depending on design characteristics and the level of integration with other transport modes. For instance, corridors with exclusive, segregated bus lanes can move more passengers in an hour than a corridor where buses operate in bus-priority lanes that also permit access to mixed traffic. Bypassing lanes at stations (which allow an arriving bus to pass those boarding passengers at the station) enable express routes to skip certain stations and reduce travel times for some passengers (Carrigan et al., 2014). A study by Velasquez et al. (2017) identified that bus headways, the length of the BRT network, fares, modal integration at stations and the average distance between BRT stations all have a statistically significant influence on the number of daily BRT passengers. The use of articulated buses provides 50% more capacity than conventional buses, and a recent study indicates a capacity of

7200 passengers per hour per lane (Peña & Moreno, 2014). However, capacity is estimated according to available space inside the bus and a minimum interval between vehicles. It ignores the dwell time (DT) at each bus stop.

Table 2.2 shows the peak load capacity for BRT with and without overtaking lanes.

Table 2.2 Peak load capacity for BRT with and without overtaking lanes
(Adapted from Carrigan et al., 2014)

Type of BRT Transit mode	Peak load factor capacity
BRT – single lane and no overtaking	Up to 13000
BRT – overtaking lanes and multiple subs stops and stations	43000 to 55710

As a rule, the higher the quality of BRT services, the faster the average operating speed, and correspondingly, the more BRT becomes time-competitive for the private car and Metrorail services (Cervero, 2013). Hidalgo and Graftieaux (2008) reviewed the BRT systems in 11 cities in Latin America and Asia, finding that average speeds increased between 15 km/h and 26 km/h following the conversion from regular services to BRT services, depending on the quality of the busway.

Table 2.3 shows the operating speeds in BRT systems with or without express services.

Table 2.3 Design operating speeds for BRT under different conditions (Adapted from Carrigan et al., 2014)

Type of BRT transit mode	Operating speed (Km/hr)
BRT on urban arterial and no express service	18–28
BRT on suburban arterials with predominately express service	28–35
BRT on an expressway (with no intersections and no express service)	40+

According to Lin and Ruan (2008), passengers are more concerned about bus headway regularity than actual punctuality of bus arrival according to the schedule. Headway irregularity discourages passengers from using public transport on frequently served bus routes (Lin & Ruan, 2008). Bus service performance may vary due to traffic conditions, operations, and passenger demand.

Levinson (1983) showed that DT was an important parameter that affects service quality, and he developed a linear model using a constant proportion related to the number of boarding passengers at a stop, which seems more consistent. According to Chien et al. (2000), DT is determined mainly by the passengers' 'activities at every bus stop'. In effect, bus stops are where the greatest proportion of the trip time is lost during passengers boarding and alighting. The time lost for doors to open and close also forms part of DT. Zhang and Teng (2013) explain that the DT usually takes a large part of bus travel time and the large variability in DT always makes an accurate prediction of arrival time difficult.

The relationship between BRT trunk corridors and urban form is sometimes not adequately considered, yet this link remains key when planning public transport systems (Ferro & Behrens, 2015). When analysing different urban forms and the need for high-capacity lines (in the form of metro-type networks), Gilbert (2008) explained that linear-shaped cities require less infrastructure-heavy public transport lines for wide territorial coverage than cities with more spread urban forms. It can be concluded that the same length of BRT trunk route will cover more of the urban area of linear-shaped cities than that of cities with more spread urban forms. In analysing Bogotá's recent changes, it can be argued that one of the problems public transport initiatives need to overcome is the lack of articulation with the existing urban structure (Ferro & Behrens, 2015).

The conceptual operational model behind most BRT systems in the urban South is generally to develop high-capacity (usually infrastructure-heavy) trunk corridors on main roads where public transport demand is highest. On these corridors, albeit dependent on the station spacing and the types of routes, speeds and capacities are theoretically higher than before (Ferro & Behrens, 2015). Feeder routes are introduced to complement these trunk routes, and they are operated on corridors with fewer passenger demands requiring little to no infrastructural investment.

2.4. OPEN AND CLOSED BRT SYSTEMS

2.4.1. General descriptions of open and closed BRT systems

When planners or government agencies plan a **BRT** system, an important decision is whether the system should be **open** or **closed** to any kind of buses. These two systems are shown in Figure 2.1.

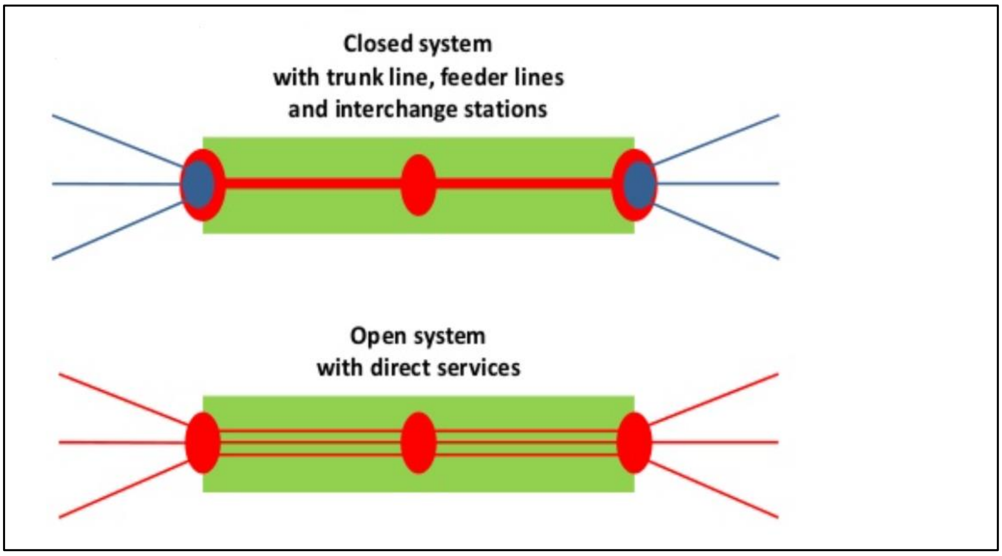

Figure 2:1 An illustration of open and closed BRT systems
(Source: UATP, October 2014)

A closed BRT system is when buses operating inside and outside the BRT trunk corridor are segregated and operate independently, such as a trunk-feeder. The allocation of different types of buses is then possible (Proboste et al., 2020). The advantage of a closed system is that it allows ease of control of the services and enforcement (Tiwari, 2014). A closed system has the following typical features (Mahadevia et al., 2012):

- segregated busways on most of the network length;
- location of the bus station and busway on the median;
- provides a good integration of network of routes and corridors;
- BRT stations that are secure and comfortable and are also protected from different kinds of weather;

- implementing pre-board fare collection system;
- integration with the feeder routes;
- entry to any other kind of bus rather than prescribed one is restricted; and
- having a distinctive marketing identity comparable to mass rapid transit systems.

Buses operating inside the corridor as the trunk routes may be larger than those operating in the feeder routes (Proboste et al. 2020). The trunk-feeder scheme induces mandatory transfers at every connecting point where the feeder lines meet the trunk lines. Transfers not only cause additional waiting and walking times but also imply the interruption of the trip, which is inconvenient (Currie, 2005). Simultaneously frequencies on the trunk lines are likely to be high, such that additional waiting could be short.

According to Gschwender et al. (2016), the case for a trunk-feeder network rests on economies of density, a property of a transport cost function understood as savings in operating costs. This saving is because of using larger vehicles in the main streets or avenues to achieve more capacity (without necessarily increasing the number of vehicles) and a cheaper cost per passenger (costs are spread over a larger passenger number). This structure seems attractive, therefore, because of the flexibility of the different fleets in terms of number of vehicles and vehicle sizes. Gschwender et al. (2016), suggests that service levels could be improved by allowing direct lines and making the system less rigid.

An open BRT system is one where bus feeder lines can enter and leave the BRT system, depending on their origin or destination so the BRT system infrastructure is shared by multiple bus types (Zhang et.al., 2020). The need for users to transfer to reach their destinations is reduced (Proboste et al., 2020). Open BRT system could be conceived in various ways; for example, with all lines departing from the origin points in the local streets and then collecting passengers along the main avenue (Diaz et al., 2015). An open BRT system has flexibility in features over the closed system. Apart from the above features, it has the following flexibilities (Mahadevia et al., 2012):

- allows existing bus routes to be included in the system;
- kerbside stops allowed to cater to the existing routes;
- any kind of bus can enter the system; and
- on-board ticketing is acceptable in this system.

According to Merkert et al. (2017), an open system has a framework where patronage is fed from neighbourhoods and funnelled onto dedicated trunk sections of the route (using the same bus).

A closed BRT system, in contrast, is where passengers take other transport services to access the dedicated BRT infrastructure and use interchanges to board vehicles using the dedicated trunk sections of the BRT system.

2.4.2. From direct to trunk-feeder – A qualitative analysis

In an urban setting, Ferro and Behrens (2015) investigated the effects of the changing relationships between paratransit operations and recently implemented BRT systems. Paratransit services are defined as a flexible mode of public passenger transport that does not necessarily follow fixed routes or schedules, typically in the form of small- to medium-sized vehicles. In the global South, paratransit services are usually provided by unregulated operators in the informal sector. The investigation focused mainly on the issues of the implementation of trunk-feeder models and the effect of including the existing paratransit services to obtain operational complementarity.

According to Ferro and Behrens (2015), the introduction of BRT systems involves the absorption of paratransit services on routes that are affected by the new project, and as a result, various strategies are used to include the existing paratransit operators. For example, in this initiative, the City of Cape Town entered long negotiations with the owners' association to get buy-in to the project. According to Salazar Ferro et al. (2012), with this approach, not all existing paratransit operators are included and typically must operate in another transport corridor to make way for the BRT system. Moving to other transport corridors is not always an option if the public transport restructuring is for the entire city (the case of Santiago). In essence, the paratransit operators experience changes as they move away from their daily practices, such as daily income, limited maintenance, and relatively informal labour relations. Operationally, it involves a shift from paratransit operators' direct services to a more formal feeder and trunk service.

The creation of direct paratransit routes is based on fluctuating and unsystematic urban growth. In the global south, where there is growth in poor residential areas located on the peripheries, this is particularly common. Cervero (2013) points out that this is due to the formal job market being primarily in the central areas, which are, therefore, a main destination points for many commuters located in low-income peripheral areas. These commuters use direct paratransit services due to the operational flexibility and demand responsiveness offered by these services.

According to Ferro and Behrens (2015), the paratransit system serviced most urban areas before implementing Transantiago's BRT in Santiago (Chile). Commuters had access to the paratransit routes (most were within 800 metres) and were serviced at high frequencies (an average headway of four minutes). However, most of these characteristics were lost after the implementation of

Transantiago in 2007. The Transantiago comprises a trunk-feeder BRT model that aims to 'formalise' existing services, reduce externalities, and optimise operational costs (Ferro & Behrens, 2015) while imposing a mandatory transfer. Regarding operating costs, it would arguably be costly to provide direct services for all origins and destinations in a city. According to Ferro and Behrens (2015), it is also estimated that approximately 60% of trips require one or more transfers because of the trunk-feeder models. In the case of Transantiago, it is unclear if the increase of trunk and feeder routes increased the coverage or not. In Bogotá (Colombia), the paratransit coverage is still relatively higher than the coverage achieved by the BRT implementation, although BRT has had positive impacts on the public transport system (Ferro & Behrens, 2015).

2.4.3. Comparing direct and trunk-feeder BRT networks

According to ITDP (2017), the two network options can be compared using the following criteria:

- fleet requirements;
- vehicle size;
- transfer and terminal delay; and
- station and platform saturation.

Fleet requirements

The BRT planning guide compares the fleet requirements for direct s versus trunk-feeder networks. When demand shows distinct peaking characteristics (in the morning and afternoon peak periods), more fleet is typically required for trunk-feeder than for direct networks. According to ITDP (2017), trunk-feeder network required two more vehicles than direct s under peaked demand. However, when the demand is flat, the fleet requirements are basically equal (ITDP, 2017).

Vehicle size

Trunk buses are generally larger, with a capacity of 120–150 passengers (ITDP, 2017). Due to the benefit of economies of scale, the longer the trunk route length relative to the total route length, the greater the vehicle size benefit of trunk-feeder networks. Larger vehicles are more efficient as they carry more passengers at a time, so the cost per passenger-kilometre is reduced (all other things being equal).

Transfer and terminal delay

Trunk-feeder networks add several types of additional delay relating to the required new transfer. Figure 2.2 shows the transfer station required for a trunk-feeder only and not for a direct network. The disadvantages of this are:

- the increased capital cost of constructing the station/terminal;
- increased passenger waiting times inside the station/terminal; and
- increased passenger walking time inside the station/terminal.

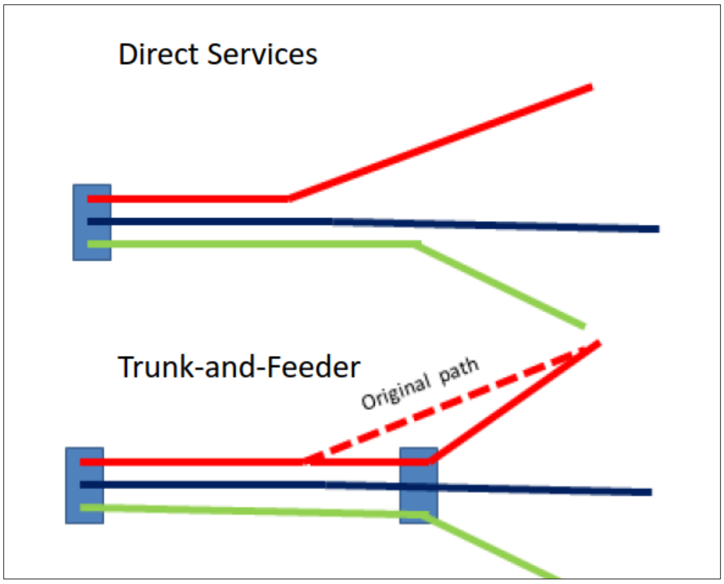

Figure 2:2 A transfer station required only for trunk-feeder network
(Source: Wright & Hook, 2007)

Station and platform saturation (demand/capacity ratio)

When deciding between direct versus trunk-feeder networks, station and platform saturation needs to be considered and avoided. Concerning station saturation, the degree to which any specific route is likely to congest or cause bottlenecks at the station must be calculated. Concerning platform saturation, increasing the bus frequency in a trunk-feeder network reduces the number of passengers waiting in a station/terminal and their waiting time, which reduces the level of saturation on the platform. According to the ITDP (2017), lower frequency, direct routes can result in more customers having to wait on station platforms than high-frequency trunk routes. For low demand systems, this does not cause any significant problem. However, at high levels of demand, the station platform can become overcrowded and saturated.

Gschwender et al. (2016) compared direct versus trunk-feeder networks using idle capacity, transfers, and economies of density (Table 2.4). Gschwender et al. (2016) also stated that direct lines exhibit idle capacity, increasing operators' costs, whereas economies of density are captured only by trunk-feeder lines. The trunk-feeder line structure is the only one that includes transfers (Gschwender et al., 2016).

Table 2.4 Comparing direct and trunk-feeder networks using idle capacity, transfers, and economies of density

(Source: Gschwender et al., 2016)

	Idle capacity	Transfers	Economies of density
Direct	Yes	No	No
Trunk-feeder	No	Yes	Yes
Impact	Increase in operators' cost	Increase waiting time Increase cycle time (ops cost) Increase in-vehicle time	Diminishes operators' costs

2.4.4. Performance indicators for BRT networks

A basic service plan should be developed before any infrastructure designs are made or finalised (ITDP, 2017). This section introduces the basic service planning concepts that are used in BRT planning and design.

Station saturation

In BRT systems, the constraint on capacity is the BRT station because, at high frequencies, a BRT station cannot process the high volume of vehicles as would a traffic signal. At the station, it needs to be considered that DTs (which is defined as the time interval between the opening and closing bus doors to serve passengers at the bus stop) play a contributing factor in the number of buses that can be processed at any given hour. Station saturation is a critical issue that needs to be solved to maintain speeds and reduce delays. The saturation level of a station refers to the percentage of time the station is occupied by vehicles boarding and alighting customers (ITDP, 2017).

According to ITDP (2017), saturation changes as the demand (arrival of vehicles) is not perfectly regular. It assumed that there is a permanent flow subject to the irregularity typically observed in a roadway or a busway. A saturation level of 0.85 is normally permitted in mixed traffic to counter this irregularity where there will be minimal impact on the average speeds. However, at BRT stations, queues and delays occur at low saturation levels and these increase with saturation (ITDP, 2017). In general, stations should be planned at less than 40% saturation (ITDP, 2017), although it can also range between 0,3 to 0,6 for optimal results and at specific locations. A low saturation level means that there is a low likelihood of vehicles waiting in a queue at a BRT stop and vice versa.

Average speed

Average speed is the distance covered per time ratio. Most commonly, the distance is calculated using GPS data or taken from the General Transit Feed Specification (GTFS). In terms of the time, a speed survey is usually conducted, and the several peak hour trips (when trips are at the maximum) are timed to get an average time value. Peak hour is used because planning decisions need to be made on the worst-case scenario, which, in this case, is the peak period. The way the peak hour is determined depends on the GTFS data that is most readily available. One way is to capture the boarding, alighting, and time at each bus stop and then the total boarding's per vehicle are calculated for each departing vehicle on a specific route. Another way the peak hour can be calculated is from frequency and occupancy counts for each bus route. In this case, a surveyor would stand at the critical link (highest demand section of the route) and count the number of buses on a specific route and estimate their occupancy. The hour with the maximum frequency and highest occupancy is roughly the peak hour (ITDP, 2017).

Load factor

The load of a given link is the number of passengers in each period. According to ITDP (2017), if no further qualifications are made, the load refers to the peak hour load. Once the peak hour load has been calculated, the consolidated boarding's, alighting's, and loads at each stop on the planned BRT corridor can be calculated by simply adding up the hourly boarding's and alighting's of all the routes. Since this is generally per direction, the unit PPHPD is used to avoid confusion, which means passengers per hour per direction. The 'load factor' is the percentage of a vehicle's total capacity that is occupied. The total load factor would consider the average load factors of all the services in the system. To determine the actual load factors, the frequency, vehicle capacity and demand are used. This also means that the load factor is easily altered by changing the frequency of the services, changing the vehicle size, or changing the routes of competing services.

Frequency and headways

The service frequency refers to the number of times a specific service is offered during a given time interval, and it is normally expressed per hour, but service frequencies can also be expressed for any time interval, such as: 'ten trips per day' or '20 trips per three-hour peak period', or even 'a quarter of a trip per minute'. According to the ITDP (2017), if no further quantifications are made, then frequency means 'the number of services provided in one hour, during the peak'. Headway is defined as the time between two vehicles offering a service and can be expressed as, for example: 'one trip every two hours' or as 'one trip every 90 minutes' or 'one trip every 30 seconds'. The mathematical relationship between headway and frequency is shown in the formula:

$$\text{Frequency} = \frac{1}{Headway} \tag{1}$$

$$\text{Headway} = \frac{1}{Frequency} \tag{2}$$

The minimum frequency, which is defined as the frequency required to service the existing demand, can be calculated using the following equation if the vehicle size is fixed and an acceptable load factor has been determined:

$$\text{Frequency} = \frac{Max\ Load}{Vsize * Load\ Factor} \tag{3}$$

Frequency = Service frequency; the number of times a specific service is offered during a given time interval.
Max. Load = Maximum hourly load on the critical link
Vsize = Vehicle capacity
Load Factor = Percentage of a vehicle's total capacity that is occupied

According to ITDP (2017), it is better to provide frequent services to reduce passenger waiting times. On the other hand, if headways are very low and frequency is very high, congestion at the station and service irregularity become a risk as the station has a certain level of capacity.

Dwell time

The Highway Capacity Manual defines DT as the duration of time that a transportation vehicle stops to serve passengers, and it includes the time between the opening and closing of doors (Transport Research Board, 2016). According to the ITDP (2017), DT consists of two separate types of delay: 'fixed dwell time' and 'variable dwell time'. Fixed DT is defined as the time in which the vehicle starts to slow down as it approaches the stop, opens its doors, allows for boarding and alighting, closes its doors, and takes off. It is regarded as fixed as it does not depend on the number of boarding's and alighting's. In some countries, it is more typical to model fixed DT as only the time at the station when a bus is opening and closing its doors. Variable DT is dependent on the number of boarding's and alighting's and the time each passenger takes. BRT systems can operate a metro-like service mainly due to the ability to reduce DT per customer from an average of five or six seconds per passenger for a typical bus service to only 0.3 seconds per customer on a Gold Standard BRT (ITDP, 2017). This reduction in time is possible if there is level boarding, offboard fare collection, multiple doors, and bigger door widths.

Headway reliability

According to Henderson et al. (n.d.), various measurement techniques are available to evaluate the performance of public transport services. These techniques include calculating the percentage of excessive headways, the average waiting time and the coefficient of variation for headways. All these techniques are useful analytical tools, but they have two major drawbacks. Some of the measures depend on the average scheduled headway: they have larger values for routes with larger headways. A comparison of routes with different scheduled headways is, therefore, not useful. The headway coefficient of variation is not represented on a normalised scale, so there is no upper boundary. It is not easy to tell how far the service diverges from the optimum. For example, the headway coefficient of variation is generally between 0 and 1 for bus routes, but at times it can exceed 1.

The coefficient of variation measures relative variation, and it is calculated using the ratio of standard deviation to the mean.

$$\text{Coefficient of variation} = \frac{Standard\ deviation}{mean} \quad (4)$$

An irregularity index is used to express the reliability of the actual headways against the scheduled headways. It is measured as:

$$Irr = \frac{Variance\ of\ the\ headway}{scheduled\ headway^2} \quad (5)$$

Where:

Irr: Irregularity index, the measure of the variance between the actual headways and the scheduled headways

Variance of the headway = Amount that the headways are spread out from the mean

Variance of the headway is statistically defined as the expected value of the squared deviation from the mean headway. When calculating the variance from a sample, it would be equal to the sum of the square of the differences between each observed headway and the average headway divided by the number of observations minus one, given by:

$$V_{headway} = \frac{\sum_{i=1}^{N_{obs}}.(headway_i - headway_{average})^2}{N_{obs}-1} \quad (6)$$

Where:

$V_{headway}$ = Variance of the headway, expected value of the squared deviation from the mean headway

N_{obs} = Number of observed headways

Headway = Observed headway for 'i'

$Headway_{average}$ = Average headway

Scheduled headway = Average interval between vehicles according to the timetable

According to the ITDP (2017), if there is no operational control system, empirical observation indicates that under many conditions, the irregularity index is around 0.3.

Operating cost models

Operating costs, or operational costs, are the expenses related to the operation of the buses. According to Del Mistro and Aucamp (2000), the operating costs can include:

- fuel costs; and
- costs related to staffing, management, maintenance, marketing, and facilities (stations, stops and depot).

Operating costs are usually obtained from the bus companies and are generally rationalised to consider the changes in overheads and staffing costs. These costs are then apportioned between cost/bus-kilometre and cost/bus/year.

Bruun (2005) developed a parametric cost model to provide both average and marginal cost estimates and compare annual operating costs for Light Rail Transit and BRT. The approach used was based on standard parametric cost modelling, often also referred to as engineering process cost modelling (Bruun, 2005).

Using the approach from Bruun (2005), the average total operating cost per bus on an annualised basis can be calculated as follows:

Total operating cost = C_{BH} (bus-hours) + C_{BK} (bus-kilometres) + C_{FS} (fleet-size) (7)

Where:

C_{BH} = Unit cost of one bus-hour of operation

C_{BK} = Unit cost of one bus-kilometre of operation

C_{FS} = Unit cost of keeping one bus available for operation for one year

According to Bruun (2005), the annual vehicle operations expense category includes operator, supervisory, and other staff wages and prorated fringe benefits, plus fuel, tires, and other support costs associated with delivering transportation. Fuel and tires are better estimated as proportional to vehicle kilometres and will be subtracted from the vehicle operations portion.

.

$$C_{BH} = \frac{Vehicle\ operations - fuel\ \&\ lube - tyres\ \&\ other}{revenue\ bus{-}hours} \quad (8)$$

The annual vehicle maintenance expense category includes labour and prorated fringe benefits, expendables and parts consumption, and support vehicle costs. Also added are the fuel and lube and tyres and other values that were subtracted from the annual vehicle operations expense.

$$C_{BK} = \frac{Vehicle\ maintenance + fuel\ \&\ lube + tyres\ \&\ other}{revenue\ bus\ kilometres} \quad (9)$$

The annual nonvehicle maintenance expense category includes upkeep of all fixed facilities, including offices, depots, and route infrastructure. General administration includes all other overheads such as senior management, planning, procurement, legal, accounting, and insurance.

$$C_{FS} = \frac{nonvehicle\ maintenance + general\ administration}{peak\ fleet\ size} \quad (10)$$

2.5. ANALYTICAL STUDIES ON DIRECT AND TRUNK-FEEDER BRT NETWORKS

According to Kepaptsoglou and Karlaftis (2009), heuristics and analytics can be used to determine the most appropriate line structure in an urban setting. Diaz et al. (2015) stated that heuristics had been developed to help with the design of real-size transit systems, while the analytical approach has proved beneficial to provide a starting point for a detailed design. Cedar (2001) stated that analytical modelling on simple networks helps the strategic design of real transit networks and policy analyses. Jara-Díaz and Gschwender (2003) did a study that extended the microeconomic framework of one line to a simple network involving non-aligned (O-D) structures and alternative spatial organisations of bus services. The objective of the study was to depart from single line analysis by exploring simple O-D networks and determining the advantages and disadvantages of direct against transfer-based line structures. It was found that direct lines were convenient in cases that could be looked at as a centre-to-periphery flow pattern. The main advantage of a direct line structure is basically the avoidance of transfers.

When a linear urban corridor with three zones (Figure 2.3) was explored analytically to determine the effect of unbalanced demand on optimal line structure, it was found that the single line structure dominated when the demand (Y1) is high over the entire corridor. The reason for this is idle capacity being diminished. It was also found that the trunk-feeder network dominated when the demand was high on the common link (b-c) because the number of transfers is reduced, and spare capacity is avoided (Jara-Díaz et al., 2012).

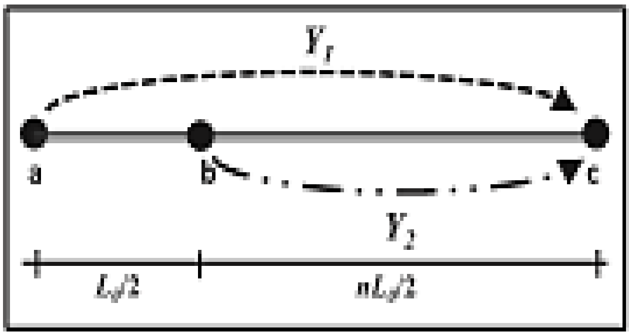

Figure 2:3 Linear corridor with three zones
(Source : Jara-Diaz, et al., 2012)

Gschwender et al. (2016) did an analytical framework to compare trunk-feeder lines with three types of direct lines using a simple network diagram where several flows converge into a main avenue (Figure 2.4). Also, the effect of total passenger volumes and the number of long trips was examined, considering the impact of a pure transfer penalty. The approach used was to develop a social cost function for a given demand and use it to minimise total costs. Trunk-feeder network is favourable for short trips and do not present idle capacity because of three conditions:

- a smaller feeder fleet can be used for low demand areas while reducing waiting times in the peripheral areas;
- the advantages of economies of density in the main avenue become relevant; and

- the number of passengers that need to transfer is low.

However, these advantages are lost when a transfer disruption is considered. For long trips, the direct lines have an advantage because of two factors: idle capacity is minimised, and transfers are not needed (an advantage over the trunk-feeder structure).

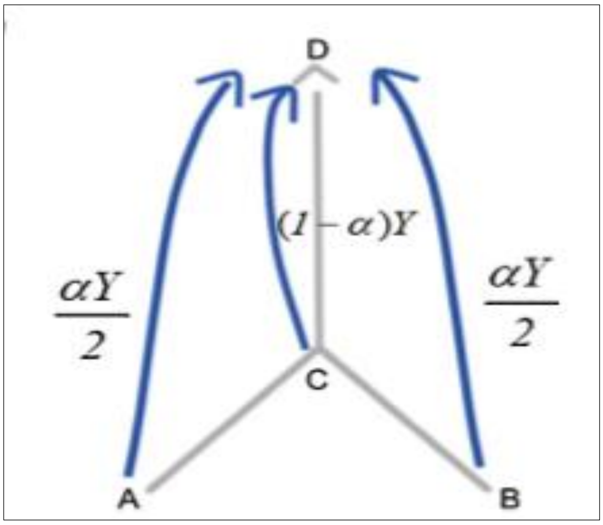

Figure 2:4 Simple network with flows converging to a common link
(Source : Gschwender et al., 2016)

Fielbaum et al. (2016) use a parametric description of urban systems based on the hierarchy of its centres and a simple representation of the network to find the optimal line structure. Better topographical indicators and different degrees of monocentricity (one centre of attraction), polycentricity (many centres of attraction) and dispersion (centres are scattered and difficult to determine) were presented. The city model is represented in Figure 2.5: this has been approached by using heuristics, solving this problem with an optimality approach. The results were that direct lines were optimal when trips were not dispersed because this structure performed badly at collecting trips. Trunk-feeder lines were dominant when the urban structure was polycentric because idle capacity was diminished and allows for a balance of fleet sizes and vehicle capacities.

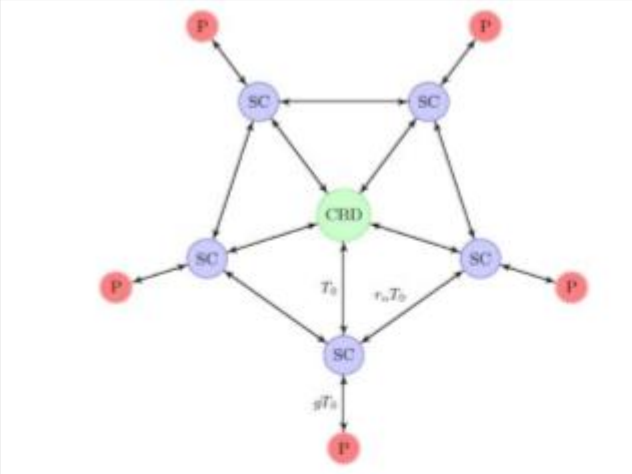

Figure 2:5 Graphical representation of a city model with monocentric, polycentric, and dispersed flows (Source: Fielbaum et al., 2016)

Proboste et al. (2020) researched the design of massive bus-based public transport systems in medium-sized cities. The research included two mathematical models built with different levels of detail in terms of a city's characteristics. The models represent both agency and user costs aiming at revealing the key parameters that determine which one is the best option for a medium-sized city. The first model was a classic idealised city approach and the second model had specific geographic characteristics and constraints of an actual city. It was assumed that the city in question would have a single bus-segregated corridor, structured as a BRT, around which all other regular bus services will be organised. Also, the characteristics of medium-sized cities included low road congestion and little bus interaction at stops. Low variability of travel times was assumed. However, this approach meant that the results obtained should be applied to cities meeting these requirements.

The results show that trunk-feeder BRT networks offer mid-sized cities higher frequencies and lower waiting times. These benefits do not cancel the cost associated with the higher number of transfers that trunk-feeder BRT networks require compared to direct BRT networks.

Del Mistro and Brunn (2012) undertook an analysis to determine the conditions where feeder and trunks will outperform direct lines regarding the cost of public transport service, passenger travel time and energy consumption. The model created considered the following:

- peak hour volume;

- route length;
- percentage of trips from origin to destination;
- peak hour public transport trip production density from origin;
- peak hour public transport trip attraction density to destination; and
- number of routes.

According to Del Mistro and Bruun (2012), the trunk-feeder solved the problem of economies of scale caused by insufficient volumes, especially from residential areas; it divides the trip into feeder, trunk and distributor carrying different volumes using different vehicle capacities. The results showed that in terms of cost, the trunk-feeder only had lower costs compared to direct in seven of the 962 cases that were analysed (0,7%), and the difference was never more than 7% (this includes both the capital and operating costs). Concerning travel time, the trunk-feeder was never found to be slower than direct. Trunk-feeder consumed less energy than direct in 756 of the 962 cases (79%).

2.6. SUMMARY

Literature is available on direct and trunk-feeder BRT networks, and different approaches have been used previously to determine the conditions in which one network is superior to the other. These studies use analytical and theoretical approaches to answer the question of direct versus trunk-feeder BRT networks. The studies provide valuable insights into the application of both types of networks. While the analytical models provide valuable insight into the comparison of direct versus trunk-feeder BRT networks, one of the main limitations of analytical approaches is that the findings are true for conditions that were investigated.

The studies first use a simple representation of the whole or a part of a city network. In some cases, small networks are used to emphasise specific aspects of the problem; for example, Y-shape (Gschwender et al., 2016) or cross-shape (Jara-Díaz and Gschwender, 2003). Trunk-feeder is considered superior for short trips because when there is a low proportion of long trips (meaning no local trips), then there would be fewer transferring passengers from the feeders to the trunk network. Also, trunk-feeder ise not ideal for long trip lengths because the operator's cost increased due to longer cycle times (including transferring time) and increased fleet size (trunk and feeder buses required). The case for the trunk-feeder network rests on economies of density, which translates as savings in operating costs. This saving results from using larger vehicles in the main streets or avenues to achieve more capacity (without necessarily increasing the number of vehicles) and a cheaper cost per passenger (costs are spread over a larger passenger number). Therefore, this structure is attractive because of the flexibility it provides in terms of vehicle sizes. With direct networks, the main advantage is that transfers are avoided. Transfers do not only disrupt a trip but also make the overall system slower (due to additional walking and waiting time). Direct networks are superior when there is a high proportion of long trips (long trip length), and this is because idle capacity is low.

This study aims to analyse the actual performance of direct and trunk-feeder BRT networks in the context of a BRT system with both networks in operation. It can also be used to validate or disprove what has been said analytically in the context of the Rea Vaya BRT system. Ultimately, this can guide public transport planners on structuring their services or at least what criteria to use.

3. ANALYSIS FRAMEWORK

This chapter provides a detailed description of the approach and reasoning applied to answer the research question. It also aims to explain the process leading up to the analytical design used in the study. The approach taken is an empirical one. The literature on bus system design suggests certain advantages of direct over trunk-feeder networks, especially for medium-sized systems with lower passenger demand. However, these theoretical and simulation studies usually make multiple assumptions and simplifications, ignoring real-world issues. There is limited literature on the comparative performance of these two networks in actual operation. This study intends to fill the gap by measuring and analysing their actual performance in the context of a single BRT system that has both network types in operation. The purpose will be to advance the understanding of the factors that drive the comparative performance of each type of network under real-world conditions and provide some guidance for future planning and design (and adaptation) of BRT systems.

3.1. STAKEHOLDER PERSPECTIVE ON DIRECT AND TRUNK-FEEDER BRT NETWORKS

The perspective of the main stakeholders and the key findings from previous analytical studies outlined in the literature review are used to structure the research questions. For this research, it is imperative to understand who the main stakeholders are and their views in terms of direct and trunk-feeder BRT networks. This research uses the City of Johannesburg Rea Vaya BRT system as a case study, and the three main identified stakeholders are the passengers, the City of Johannesburg (owner of the system) and the bus operating companies. Qualitative open-ended interviews were conducted with various stakeholders to capture the stakeholders' perspectives. The City of Johannesburg Transport Department, the Rea Vaya operator (Litsamaiso), a Rea Vaya regular user and transport planning specialists were interviewed.

The discussion with the City of Johannesburg Transport Department centred on the planning of the system and the relationship with the bus operators, and issues relating to the operation of the system. The discussion also gave insights into the role of the city as the owners of the system and their expectations. The interview with the operator concerned the service level agreement that they have with the City of Johannesburg. The interview aimed to get an in-depth understanding of the day-to-day management of operations and associated costs. Also, this was an opportunity to hear the views of the operator on direct and trunk-feeder BRT networks. The interview with the user of the system was to get insight into the overall perception of the system and what their views are on transferring from trunk to feeder buses (and vice versa). The questions with the transport planning specialists were specifically on direct and trunk-feeder networks and the indicators they deemed suitable for a comparative analysis. A list of interview questions is documented as part of Appendix A.

The passenger's views are all related to the trip utility and how they can maximise their trip utility. Passengers want a system that is reliable, safe, accessible, and cost-effective, and they want to get from origin to destination in the quickest and most convenient manner. Passengers are considered a main stakeholder because they are the users and the critical drivers of revenue in a public transport system.

The owners focus is mainly on minimising the capital and operating costs to reduce the subsidies required while still providing the necessary services. They also want to maximise the fare revenue by providing the best value for money and services to passengers, ensuring integration between land use and transport and making public transport accessible to all (ensuring connectivity within the city). Further, with the global environmental crisis, cities have become increasingly invested in reducing the carbon footprint. The bus operator's views are focused more on providing the resources to operate the system as per the service level agreement with the owner. They focus on minimising the operating costs to maximise their profit. Schedule adherence, reliability and availability are essential from an operator's side to avoid penalties (per the service level agreement). Table 3.1 shows the different indicators that are important for passengers, owners, and bus operators.

Table 3.1 Perspective of the critical stakeholders for this study

Passenger's perspective	Owner's perspective	Bus operator's perspective
Safety	Capital costs	Operating costs
Accessibility	Operating costs	Maintenance of fleet and infrastructure
Trip time	Revenue and subsidy	Operating facilities
Trip cost	Modal integration and planning	Service agreement with owner
Waiting time	Management of bus operator	Reliability
Number of transfers	Fare collection and management	Availability
Comfort	Patronage	Schedule adherence
Reliability		

3.2. ANALYSIS APPROACH

The decision of whether to operate a BRT system as a trunk-feeder network versus a direct network can significantly affect the performance of the corridor. The indicators affecting the main stakeholders have been tabled above. While each main stakeholder has their own perspective, issues around the system's performance (how efficient the service is) are mutual across all three stakeholders. According to Carrigan et al. (2014) and Herrera et al. (2016), high quality and performance are related to how BRT systems are designed. For a fast service:

- the operating speed needs to increase;
- the buses need to pass by more frequently; and
- headways need to be as regular as possible for better reliability.

As stated in the previous chapters, theoretical research (through analytical and qualitative approaches) has been conducted on direct and trunk-feeder networks. The five key issues that were identified in guiding the comparative analysis are:

- reliability
- saturation levels
- speed
- Load factor
- operating costs

These issues have led to the formulation of five hypotheses to be tested in a bid to prove (or disprove) the hypotheses and make reasonable recommendations.

Hypothesis 1: *Trunk-feeder BRT networks have more headway regularity than direct BRT networks*

According to a study by Lin and Ruan (2008), on frequently served bus routes, passengers are more concerned about bus headway regularity than actual punctuality of bus arrival according to the schedule. Headway irregularity discourages passengers from using public transport (Lin & Ruan, 2008). Headway irregularity directly impacts passengers' waiting time and hence is a key element of BRT reliability and performance. The mixed traffic operations that a direct network is subjected to introduce several external factors such as congestion, malfunctioning traffic signals, and incidents on the road, which may affect the travel time, travel speed and schedule adherence. Also, high frequencies may trigger queueing at stops and stations, affecting in-vehicle travel times: this is especially true in the case of the direct BRT, where the aggregated frequency over the corridor can become relatively high. From an operator and owner's point of view, when the headways are regular, the service is more reliable, resulting in improved fleet management, schedule adherence and efficiency.

Kathuria et al. (2017) conducted a study where two routes in Ahmedabad, one segregated BRT and the other unsegregated with conventional buses moving on it, were selected to compare headway regularity. The headway coefficient of variation was an average of 0,34 and 0,38 for a segregated and a non-segregated BRT, respectively. The coefficient of variation (CV) is the ratio of the standard deviation to the mean. It considers the scale of the data set, whereas the standard deviation does not (CV is inversely proportional to the mean).

The BRT planning guide introduces the irregularity index (Irr), which is a number that expresses the reliability of actual headways against scheduled headways. It is defined as the variance of the headway divided by the square of the scheduled headway. An irregularity index of zero means that vehicles arrive at the same headway (for Irr to be zero, the variance must be zero, meaning the observed headways are the same). The higher the irregularity index, the higher the variance of the headway in relation to the scheduled headway. There is no upper boundary for this index. The coefficient of variation and the irregularity index are similar because one uses standard deviation and the other uses variance, and both standard deviation and variance are the most used measures of spread. In essence irregularity index is the square of coefficient of variation, if the average observed headway is equal to the observed headway. Typical values from empirical studies are 0,3 (ITDP, 2017). Equation 5 is used to calculate the irregularity index.

The following shows how the metric Irr (Equation 5) can be deduced mathematically and subsequently calculated using data on several observed headways. If the average observed headway is equal to the scheduled headway (that is, that the total number of vehicle arrivals per period is as scheduled) and defining xi as the observed headway and x as the average observed headway:

$$\text{Irr} = \frac{Variance\ of\ headway}{scheduled\ headway^2}$$

$$= \frac{1}{n-1}\sum_{i=1}^{n}(\text{xi} - \text{x})^2 / \text{x}^2$$

Let variance be denoted by S^2

So, $S^2 = \frac{1}{n-1}\sum_{i=1}^{n}(\text{xi} - \text{x})^2$

Let $\sum_{i=1}^{n}(\text{xi} - \text{x})^2$ be denoted by S_{xx}

$$S_{xx} = \sum_{i=1}^{n} (\mathrm{xi} - \mathrm{x})^2$$
$$= \sum_{i=1}^{n} (\mathrm{xi} - \mathrm{x})(\mathrm{xi} - \mathrm{x})$$
$$= \sum_{i=1}^{n} (\mathrm{xi}^2 - 2\mathrm{xi.x} + \mathrm{x}^2)$$
$$= \sum_{i=1}^{n} \mathrm{xi}^2 - 2\mathrm{x}\sum_{i=1}^{n}(\mathrm{xi}) + \mathrm{x}^2\sum_{i=1}^{n} 1$$
$$= \sum_{i=1}^{n} \mathrm{xi}^2 - 2\mathrm{x}\sum_{i=1}^{n}(\mathrm{xi}) + \mathrm{x}^2 . n$$

But $\mathrm{x} = \frac{\sum_{i=1}^{n}(\mathrm{xi})}{n}$

$$S_{xx} = \sum_{i=1}^{n} \mathrm{xi}^2 - 2\frac{\sum_{i=1}^{n}(\mathrm{xi})}{n}\sum_{i=1}^{n}(\mathrm{xi}) + \left(\frac{\sum_{i=1}^{n}(\mathrm{xi})}{n}\right)^2 . n$$
$$= \sum_{i=1}^{n} \mathrm{xi}^2 - 2\frac{\sum_{i=1}^{n}(\mathrm{xi})}{n}\sum_{i=1}^{n}(\mathrm{xi}) + \frac{\left(\sum_{i=1}^{n}\mathrm{xi}\right)^2}{n^2} . n$$
$$= \sum_{i=1}^{n} \mathrm{xi}^2 - 2\frac{\left(\sum_{i=1}^{n}\mathrm{xi}\right)^2}{n} + \frac{\left(\sum_{i=1}^{n}\mathrm{xi}\right)^2}{n}$$
$$= \sum_{i=1}^{n} \mathrm{xi}^2 - \frac{\left(\sum_{i=1}^{n}\mathrm{xi}\right)^2}{n}$$

$$S^2 = \frac{\sum_{i=1}^{n} \mathrm{xi}^2 - \frac{\left(\sum_{i=1}^{n}\mathrm{xi}\right)^2}{n}}{n-1}$$

$$\mathrm{Irr} = \frac{\sum_{i=1}^{n} \mathrm{xi}^2 - \frac{\left(\sum_{i=1}^{n}\mathrm{xi}\right)^2}{n}}{n-1} \div \frac{\left(\sum_{i=1}^{n}\mathrm{xi}\right)^2}{n^2}$$

$$\mathrm{Irr} = \frac{n^2\left(\sum_{i=1}^{n} \mathrm{xi}^2 - \frac{\left(\sum_{i=1}^{n}\mathrm{xi}\right)^2}{n}\right)}{(n-1)\left(\sum_{i=1}^{n}\mathrm{xi}\right)^2} \quad (11)$$

***Hypothesis 2**: Trunk-feeder BRT networks have higher saturation levels at the station*

The capacity constraint for BRT systems is the BRT station (ITDP, 2017). In the case of a bus station, saturation level is defined as the percentage of time that the station is occupied by vehicles boarding and alighting passengers. A low saturation level implies that there is a small likelihood of vehicles waiting in a queue at a BRT station because fewer vehicles occupy the station. A high saturation level means that there will probably be long queues at stopping bays in the station as more vehicles occupy the station and for longer intervals. It is expected that the trunk-feeder BRT network will have a higher saturation level because the DTs are presumably longer as passengers must transfer from a feeder bus into a trunk bus (and vice versa). Station saturation might either be exacerbated or mitigated using different vehicle sizes. Smaller vehicle sizes in the case of feeders might increase frequencies and contribute to higher station saturation for the closed network. On the other hand, direct networks might require larger fleet sizes due to a reduced possibility of using articulated vehicles on the trunk, thus raising the number of vehicles stopping at the station and increasing station saturation levels. It is important to control for vehicle sizes when calculating saturation metrics.

Based on the definition of saturation level, a basic formula was developed for this study and used to calculate station saturation. This formula was derived to calculate the percentage of time in an hour that the station is occupied, with a specific focus on the bus docking area (for this study it is referred to as the 'kerb length') where buses stop or even queue for passengers to board and alight.

For this study, the saturation level will be calculated separately for trunks, feeders, and complementary buses. This method allows for separability in cases where more than one type of bus has docked at the same time, especially at stations with than one docking bay and at stations where different bus types share the same docking bay. Since station saturation level in this instance is defined as the fraction of time that the station docking bay is occupied by buses per hour, then total saturation level will be the sum of the fractions that the kerb length is occupied by the different route types (trunk, feeder and complementary). This is because the same kerb length is shared by the different bus types.

The formula was developed as follows:

The kerb length is defined as the total length allocated for buses to stop at the station. Depending on the number of doors available at the station, this length can be used by buses that are currently docking (allowing for passengers to board and alight) and by buses queueing for their turn to dock (Figure 3.1).

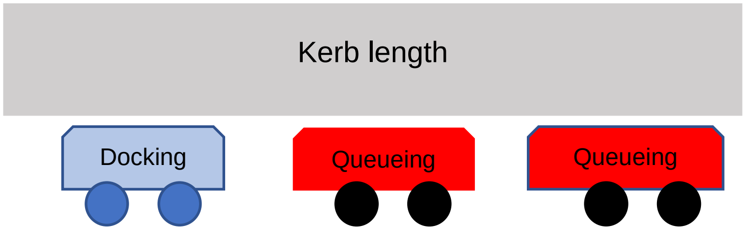

Figure 3:1 Graphical representation of the kerb length at the stations

The available kerb length per hour is calculated using the following equation:

$$K_h = K_L * 60 \quad (12)$$

Where:

K_h = Hourly available docking length (time space measurement) (metre-minutes)

K_L = Kerb length (space allocated for buses to stop at the station) (metre)

The available bus space per hour is calculated using the following equation:

$$B = \frac{Kh}{BL} \quad (13)$$

Where:

B = Hourly available space for a bus on the kerb length (bus-minutes)

B_L = Bus length (metre)

The total docking time for the buses is calculated using the following equation:

$$D_T = N_B * DT_{avg} \quad (14)$$

Where:

D_T = Total docking time per hour (bus-minutes)

N_B = Number of buses per hour

DT_{avg} = Average DT (minutes)

Docking time is defined as the time per hour that buses occupy the kerb length while allowing passengers to board and alight.

The total queueing time for the buses is calculated using the following equation:

$$Q_T = N_B * QT_{avg} \quad (15)$$

Where:

Q_T = Total queueing time per hour (bus-minutes)

N_B = Number of buses per hour

QT_{avg} = Average queueing time (minutes)

Queueing time is defined as the time per hour that the buses occupy the kerb length while queueing.

The total time spent by a bus at the docking area per hour is calculated by:

$$T_t = D_T + Q_T \quad (16)$$

The fraction of time that a specific bus type t occupies the station is calculated using the following equation:

$S_t = T_t / B$ (17)

The total saturation level at the station will be as follows:

$S_T = S_{tT} + S_{tF} + S_{tC}$ (18)

Where:

S_T = Total saturation level

S_{tT} = Saturation level for trunk buses

S_{tF} = Saturation level for feeder buses

S_{tC} = Saturation level for complementary buses

According to ITDP (2017), saturation levels of around 0,3 are arguably considered optimum; however, saturation levels of 0,4 to 0,6 can be tolerated, based on the conditions of the station and location. It should be noted that saturation levels affect the level of service at the station, so the higher it is, the more likelihood of delays and queueing at the station. A saturation level of 1 (or 100%) would mean that the docking area is continuously occupied (maximum capacity).

Hypothesis 3*: Direct BRT networks lower overall travel times by avoiding transfers, compared to trunk-feeder BRT networks, resulting in higher speeds*

According to Proboste et al. (2020), the number of transfers that a trunk-feeder configuration requires creates several operational inefficiencies due to considerably higher DTs. Longer DTs in the case of a trunk-feeder BRT network (due to the transfer) also affect the commercial speed of the buses. The number of transfers in the closed BRT network also make in-vehicle travel time longer than the open BRT network.

For the comparative analysis, the vehicle operating speed and passenger speed will be used. The following equation will be used to calculate the average vehicle operating speed:

$S = \frac{D}{T}$ (19)

Where:

S = Vehicle operating speed km/h

D = Route distance from start to the end of the route km

T = Travel time from start to the end of the route h

The travel time includes the DT at the stops but does not include terminal time at the end of the trip before starting the next trip.

The following equation will be used to calculate the passenger trip speed:

$$ST = \frac{TD}{TT} \quad (20)$$

Where:
ST = Passenger trip speed
TD = Trip distance
TT = Trip time

Trip distance is defined as the distance from when the passengers enter the BRT system to when they exit. Trip time is defined as the time the passenger enters the BRT system to when they exit the system.

Hypothesis 4: *Trunk-feeder BRT networks have a higher load factor than direct BRT networks*

The load factor as an indicator shows the average load on a bus route throughout the day as a proportion of the bus capacity. The trunk-feeder BRT network is flexible in that different fleet sizes can be used for different demands (Fielbaum et al., 2016). Thus, by using large trunk buses in the dense environment of the corridor and smaller feeder buses outside it, supply can better fit the demand, which would result in higher average load factors. With a direct BRT network, the same bus capacity is provided for the entire trip. The mismatch of bus size and demand observed in direct BRT networks is primarily due to the same fleet being used for different demands across the route.

To determine the actual load factors, the frequency, vehicle capacity and demand is used:

$$LF = \frac{Pax\ Km}{P\ km} \quad (21)$$

Where:
LF = Load factor
Pax km = Passenger-kilometres
P km = Place-kilometres

The easiest way to measure passenger-kilometres is to conduct a sample boarding and alighting survey and to multiply the occupancy between any two stops by the stop distance.

Place-kilometres are measured as the kilometres operated by all the buses on a route multiplied by the average capacity of the buses on the route.

$$P\ km = Kb * Cp \tag{22}$$

Where:

Kb = Kilometres operated by the buses

Cp = Capacity, calculated by multiplying vehicle size by the frequency

The load factor is, therefore, calculated as a proportion of the demand in relation to the capacity.

Hypothesis 5: *Trunk-feeder BRT networks have reduced operating costs compared to direct BRT networks*

The theory holds that trunk-feeder networks may have lower operating costs due to the possibility of using smaller vehicles on the feeder routes and larger vehicles on trunks, thus matching supply more closely to demand on different sections of the route. A logistic cost model is created considering all the input costs that make up the operating costs to first model the existing routes of each type.

An operating model was developed to compare the operating costs per bus-kilometre and the cost per passenger for trunk, feeder, and complementary routes of the Rea Vaya BRT system. The model considers the bus and driver cost and excludes facilities and station costs as well as general staff costs as these costs are shared by all the route types.

For this study, the total operating costs are made up of vehicle operating costs and driver costs per month for November 2019, on weekdays only.

For vehicle costs, the following will be considered: maintenance costs, tyre costs and insurance. Concerning capital costs, the purchase price for the different bus sizes will be sourced from the City of Johannesburg. The capital cost will be amortised over the six years to determine the monthly repayments.

For driver costs, the following will be considered: labour, leave allowance, UIF allowance, training, and uniform.

In this study, two measures will be considered: operating costs per kilometre and cost per passenger. The operating cost per kilometre will be calculated separately for all the trunk, feeder and complementary routes based on their operations (the types of bus uses, route length, and number of trips per day, among others). The trunk and feeder buses will represent the trunk-feeder network, and the direct network will be represented by the complementary buses. The cost per passenger will also be calculated separately for all the trunk, feeder and complementary routes, and the unit will be rand/passenger. To control for other factors affecting costs, which have nothing to do with direct versus trunk-feeder, a counterfactual analysis approach was used to model the opposite.

3.3. POSSIBLE CONSTRAINTS FOR MEASURING THE INDICATORS

While the indicators are meant to be used in the comparative analysis of direct and trunk-feeder BRT networks, a few complications are expected when applying them. This is due to factors such as the operating environment that may be unique to the Rea Vaya BRT system. The constraints are:

- Time-of-day variations – Most of the indicators are expected to vary across peak and off-peak hours because of issues such as congestion, demand, and frequencies that are different across peak and off-peak periods. Comparing peak, off-peak, and all-day averages will be useful in understanding contextual differences.
- Separability – Since the case study is based on a BRT with both direct and trunk-feeder networks in operation, it may be complex to observe the differences, especially in cases where there is an overlap. For example, when looking at the operating costs, it is crucial to control other factors affecting costs that have nothing to do with direct versus trunk-feeder. A counterfactual approach would be necessary to model the opposite.
- Data availability – The availability of data is a constraint for the study. For instance, the amount of information available is dependent on the technologies deployed. For example, GPS data could not be obtained. The use of different data sources helped close the gap in the case of missing or inadequate data.

4. DATA COLLECTION METHODOLOGY

The case study is based on the City of Johannesburg's Rea Vaya BRT system, where both types of networks (direct and trunk-feeder) are in operation. Data collection is from four sources: station surveys and observations, on-board surveys, ticketing information, and system data (schedules, operating costs, stop locations) sourced from the operator and the City of Johannesburg.

Case study research calls for selecting a few examples of the phenomenon to be studied and then intensively investigate the characteristics of those examples. A case study methodology is well suited for this research, as direct and trunk-feeder BRT networks can be observed in operation and contextualised in the case of Rea Vaya and the City of Johannesburg. Table 4.1 shows the advantages and disadvantages of case study methodology. The main limitation of a case study approach is the potential inability to apply the conclusions to systems beyond those studied.

Table 4.1 Advantages and disadvantages of case study methodology
(Source: Johansson, 2003)

Advantages	Disadvantages
Allows for extensive detail to be collected	Data collected can sometimes not be generalised as it relates to specific conditions
Scientific experiments can be conducted	Some cases are not scientific
Freedom to collect multiple kinds of information	Bias in the researcher can influence the results
	Validity of the data can be an issue

Case study methods enable collecting detailed data and using a mixed-method analysis to extensively explore the issues related to the operation of direct and trunk-feeder BRT networks. It is, therefore, considered a suitable methodology for this research.

4.1. CASE STUDY INTRODUCTION

The City of Johannesburg is a vibrant and culturally rich metropolitan city situated in the Gauteng province, the economic hub of South Africa (see Figure 4.1). Gauteng is the smallest province of the nine provinces in South Africa, but it comprises the largest share of the South African population. According to the City of Johannesburg 2017/18 Integrated Development Plan (IDP), the city was home to 4.9 million people as of 2016, making it the largest metro in South Africa.

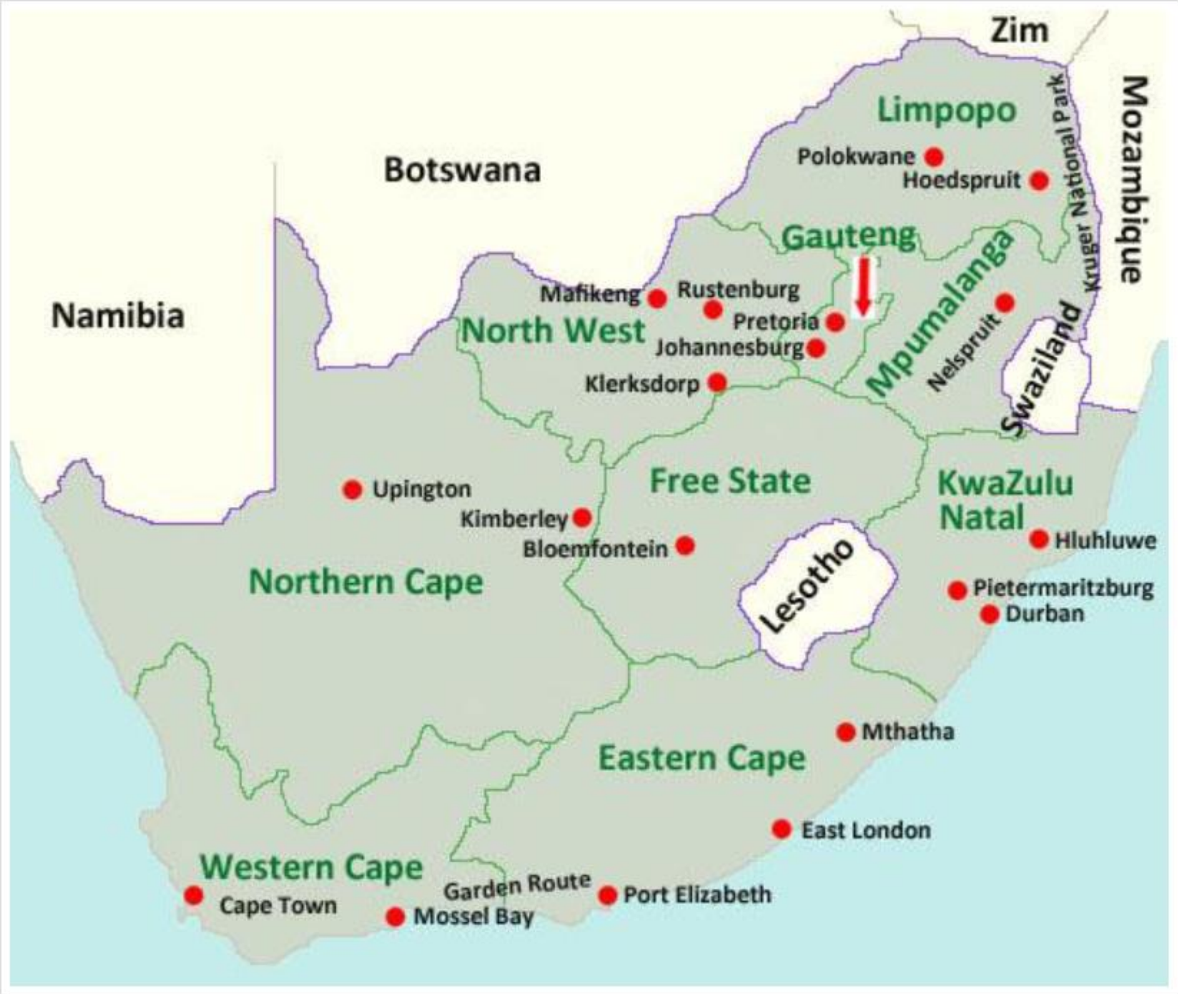

Figure 4:1 Map of South Africa showing the nine provinces
(Source: https://showme.co.za/facts-about-south-africa/the-maps-of-south-africa/)

Due to urban sprawl and the growing economy, it is projected that the population could increase from 4.9 million (2016) to 5.4 million by 2021 and 7.6 million by 2037. In terms of the broader South African context, Johannesburg makes up 36% of the population in Gauteng and 8% of the population in South Africa (City of Johannesburg, 2017/18). The City of Johannesburg, like many of the cities in South Africa, is affected by apartheid era spatial planning where black people were segregated and intentionally located in high-density peripheral areas away from economic benefits. As is the case with many big cities globally, the city is overwhelmed by economic migration, which has increased the need for mobility and constraints on the current system.

The demographics of Johannesburg indicate a large and ethnically diverse metropolitan area. The most common racial groups in Johannesburg are Black African (76.4%), Coloured (5.6%), White (12.3%) and Indian/Asian (4.9%). Sixty-eight point nine per cent of the population is between 16 and 64, 25.7% are under the age of 15, and the rest are over 65 years old. In terms of the sex ratio, there are 100.3 males per 100 females. South Africa has suffered from a high level of unemployment and, according to the Quarterly Labour Force Survey released by Statistics South Africa (February 2019), the unemployment rate is 27.1%, a slight drop from 27.5% in the last quarter of 2018; this has contributed to high levels of crime and poverty. Johannesburg has high unemployment levels and poverty and one of the highest levels of inequality in the world. Of the economically active population in Johannesburg, 72% are employed (1 696 520 people) while 28% are either unemployed (564 970 people) or discouraged work seekers (105 882 people) (City of Johannesburg, 2013).

4.1.1. Mobility in Johannesburg

There are alternative modes for public transport in Johannesburg, including Metrorail, Gautrain, Rea Vaya, Metrobuses, PUTCO and minibus taxis.

Metrorail is a commuter rail operator in Johannesburg run by the national Passenger Rail Agency of South Africa. The rail network connects the three main metros in Gauteng (the Cities of Tshwane, Johannesburg, and Ekurhuleni) and Figure 4.2 shows the train and the infrastructure it uses. However, the network does not fit entirely with the present-day residential and economic nodes and coupled with many years of no investment, the rail system offers poor quality service (City of Johannesburg, 2013).

Figure 4:2 A train operated by the Passenger Rail Agency of South Africa

Gautrain is an 80-kilometre commuter rail system in Gauteng, South Africa, which links Johannesburg, Pretoria, Ekurhuleni and the OR Tambo International Airport. It is a provincially implemented, modern high-speed rail service that offers a fast, convenient, safe, and efficient public transport service. The objective of the Gautrain was to provide a quality intercity and airport service and to attract private car users to public transport. Figure 4.3 shows an image of the world-class train system.

Figure 4:3 Rapid rail system in Gauteng Province (Gautrain)

Rea Vaya is a BRT system operating in Johannesburg, South Africa; it opened in phases starting on 30 August 2009. Rea Vaya links the Johannesburg Central Business District (CBD) and Braamfontein with Soweto. Figure 4.4 shows an example of the vehicle and the median-based station used on the Rea Vaya system.

Figure 4:4 Trunk bus on trunk infrastructure

Metrobus was set up as a company in 2000 and is wholly owned by the City of Johannesburg. It is a municipal bus operator in Johannesburg, with a variety of buses ranging from double-deck, single-deck buses equipped with hydraulic lifts for wheelchairs, open deck, and luxury coaches. Figure 4.5 shows an image of a single-deck Metrobus. Metrobus covers 330 scheduled routes and 128 school routes. The city appointed Metrobus in terms of the Service Delivery Agreement to provide bus transportation services to Johannesburg residents.

Figure 4:5 Metrobus single-decker

The Public Utility Transport Corporation, also known as PUTCO, is a provider of commuter bus services in the provinces of Gauteng, Limpopo, and the western parts of Mpumalanga in South Africa. It is privately owned and has a fleet of 1 400 buses, transporting more than 210 000 passengers daily. Figure 4.6 shows one of the PUTCO buses.

Figure 4:6 PUTCO single-decker bus

The minibus taxi industry in South Africa is today the most critical pillar of the public transport sector. The sector emerged in the wake of the apartheid government's economic deregulation policy, initiated in 1987. Not only is it the most available mode of transport, but it is also the most affordable for the public. According to the National Land Transport Act of 2009 in South Africa, a minibus is a vehicle that has a capacity of between seven and 16 passengers. In Johannesburg, this sector accounts for 50% of motorised trips (Scorcia & Munoz-Raskin, 2017). Figure 4.7 shows an image of minibus taxis operated in Johannesburg.

Figure 4:7 16-seater minibus taxis

However, with so many options, there are still challenges facing public transport, including the following (Gauteng Provincial Government, 2013):

- car ownership is on the increase, which can be closely correlated to car use;
- in the past ten years, only Rea Vaya and Gautrain were introduced, and due to geographic reasons, they currently serve a small market;
- the Metrorail and bus services are deteriorating in terms of reliability, safety, and quality; and
- inconsistencies in the taxi recapitalisation project.

As a result of the high private vehicle use, mobility in the city is affected negatively. The roads are congested, resulting in long travel times. Challenges with the Gauteng Freeway Improvement Project and e-tolling increase pressure on the roads as no new highways are being built. By looking into the detail of Johannesburg's public transport distribution, as shown in Figure 4.8, the informal minibuses (known locally as taxis) carry 50% (or more) of motorised trips. The other 50% is split into 32% Metrorail, 6% subsidised commuter bus services (including PUTCO), 5% formal urban public bus service (Metrobus), 4% Gautrain and 3% Rea Vaya (Scorcia & Munoz-Raskin, 2017). Before the introduction of the Rea Vaya BRT system, urban transport was dominated by paratransit, mostly consisting of minibuses.

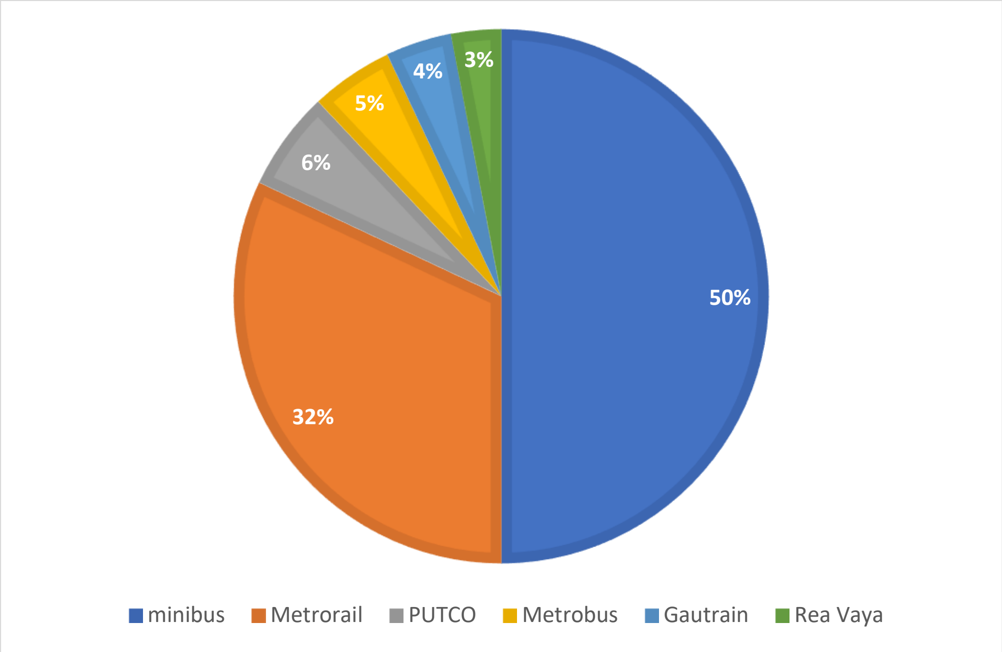

Figure 4:8 Modal split in Johannesburg
((Source: Scorcia & Munoz-Raskin, 2017)

4.1.2. Rea Vaya BRT system

The Rea Vaya BRT system in Johannesburg was the first full specification BRT system implemented on the African continent. The decision by the City of Johannesburg to implement BRT is part of its contribution to making Johannesburg a world-class city. BRT's key objectives were facilitating and promoting economic growth, poverty alleviation, restructuring the apartheid city, sustainable development, and good governance (Allen, 2013). According to the City of Johannesburg, the BRT objective is safe, reliable, and affordable public transport while promoting spatial restructuring, mobility, and accessibility. The original plan was to integrate the system with various other services, including feeder vehicles, pedestrian corridors, bicycles, metred taxis, and private vehicles (City of Johannesburg et al., 2006).

In South Africa, an Integrated Transport Plan (ITP) is a statutory plan required by the National Land Transport Act No. 5 of 2009 and the Gauteng Transport Framework Revision Act, Act No. 8 of 2002 to guide transport development and operations in the cities. The plan also forms an integral component of the IDP that the cities prepare every five years. In 2003, the City of Johannesburg formulated an ITP that was approved by the province and the Minister of Transport. The ITP was valid from 2003–2008, and it consisted of a strategic public transport network (SPTN) that prioritises public transport, minibus taxis and buses, improvements to kerbside lanes, modest infrastructure for commuters, better signage, and improved passenger information.

However, the improvements proposed by the SPTN did not create a proper public transport network across the city: they only improved the functioning environment for the minibuses with no real operational changes. The City of Johannesburg also decided to start operating the Metrobus service from Soweto to Johannesburg, which resulted in dissatisfaction between stakeholders such as city authorities and taxi unions, who felt that they had not been properly consulted in a bid to effect this change. According to Allen (2013), the City of Johannesburg found itself still in a predicament to:

- provide mass transit to its commuters;
- provide a public transport network that connects the elements of the city; and
- provide an integrated public transport solution with the involvement of all stakeholders, including taxi unions.

This was the situation until the City of Johannesburg became aware of the transport system in Bogotá, Columbia, and the idea to implement a BRT in Johannesburg was born. The BRT in Johannesburg was planned as the backbone of a future transport system interconnected with rail to provide high levels of accessibility and capacity.

The original SPTN corridor structure is illustrated in Figure 4.9.

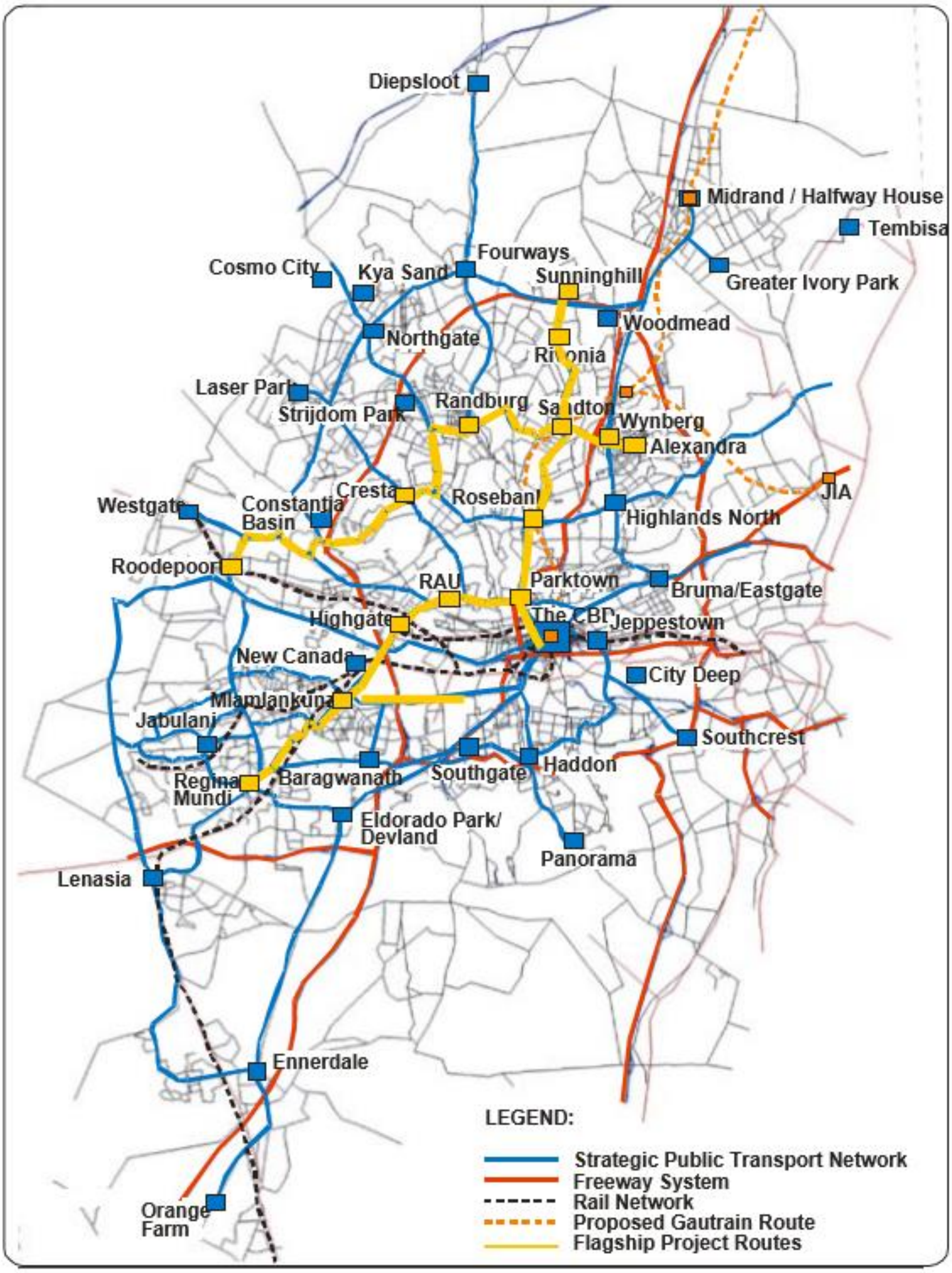

Figure 4:9 Original SPTN network
(Source: City of Johannesburg et al., 2006)

According to Wood (2015), BRT first arrived in its current form in South Africa in July 2006 at a special session of the Southern African Transport Conference (SATC), the largest transport convention in the region. In this specific SATC, the National Department of Transport invited global BRT expert Lloyd Wright to share his knowledge of BRT's fundamental principles and engineering specifications. Later in the same year, a series of workshops were held in major cities in South Africa, including Johannesburg, specifically targeting politicians and transport planners. Inspired by these presentations, Johannesburg planners and politicians travelled to Bogotá (Colombia) and Guayaquil (Ecuador) in August 2006 to see these systems in operation. One of the key lessons from Bogotá’s TransMilenio was the need to establish a strong identity and brand image for the BRT system; hence, the name 'Rea Vaya' ('We are Going' in Scamto[2]) was chosen in the Johannesburg BRT branding campaign. Three years later, in August 2009, Rea Vaya opened in Johannesburg as the first fully featured BRT on the African continent, promising to herald a new era in South African public transport.

According to the City of Johannesburg et al. (2006), in terms of route and corridor structure, the City of Johannesburg BRT plan is not significantly different to the SPTN, and it builds on the work that has been applied to the SPTN. The major changes from the SPTN to the Rea Vaya BRT system were the upgrading of the physical infrastructure, operational characteristics, and business model. The principal physical differences between SPTN and BRT are:

- median busways instead of kerbside bus lanes (the median busways avoid conflicts with left-turning mixed traffic and thus substantially improve travel times);
- pre-board fare collection and fare verification (which reduces vehicle waiting times at stations);
- larger vehicles (vehicle size will be closely matched to actual demand to ensure frequent and profitable services); and
- a centralised vehicle control centre.

Rea Vaya routes have three classifications: trunk, complementary, and feeder routes. Trunk routes (T) use dedicated median-exclusive busways located between mixed traffic lanes (see Figure 4.10), with closed median stations that allow level boarding. Complementary routes (C) use a combination of normal mixed traffic roads and dedicated median-exclusive busways. Complementary routes connect major passenger origins and destinations, served by buses able to interface with both kerbside Rea Vaya bus stops and median Rea Vaya stations. They serve to improve the system coverage. Feeder routes (F) start and end at Rea Vaya trunk stations using normal mixed traffic roads, connecting areas of significant passenger origins to trunk and complementary routes. These routes increase the catchment area.

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[2] Scamto is a township language used in South Africa and is a combination of the country’s 11 official languages.

Figure 4:10 Median bus lanes for BRT in Johannesburg

The City of Johannesburg has approved an Integrated Public Transport Network (IPTN) to guide the delivery of the City's public transport system. The IPTN, as presented, is made up of six types of network artery, which are described in more detail in Table 4.2. For each type of artery, the typical volume of passengers to be serviced is shown, together with associated public transport modes envisaged to operate. The design objective is to guide the implementation of an IPTN that is truly responsive to the transport system sustainability goals, aiming to provide access to public transport, promote green environmentally friendly transport, and maximise public transport service cost recovery.

Table 4.2 Modal hierarchy framework per the IPTN

Type of Service	Description of typology	Peak demand (passengers per hour)	Examples of Modes	Function in the network
Type A	Rail Public Transport Network	9 000–15000	Gautrain, Metro Rail	Moves people quickly from areas of high residential density to areas of employment/income opportunities. Limited stops Closed stations
Type B	Rapid Road Public Transport Network (High Capacity)	6 000–9 000	Bus Rapid Transport, Light Rail, Rapid rail	Services Corridors of Freedom, mixed-use development, three-story residential. Moves people quickly from areas of high residential density to areas of employment/income opportunities. Limited intersections and right turns so buses can be relatively speedy. Limited mostly closed high or low floor stations.
Type C	Road Public Transport Network (Medium Capacity)	3 000–6 000	Bus Rapid Transport	Corridors of Freedom and areas where the city wants to densify along the corridor. Mixed-use development, three-story residential, social housing along corridor. Fairly frequent closed and open slow floor stations and some stops.
Type D	Road Mixed Traffic Public Transport Network (Medium to Low Capacity)	1 000–3 000	Bus (Double Decker, Standard)	Frequent stops with shelters Some public transport priority (for example, queue-jumping). On-street stopping by public transport vehicles. Low to medium density.
Type E	Road Mixed Traffic Public Transport Network (Low Capacity)	500–1 500	Bus (Standard, Minibus)	Frequent stops with laybys and shelters Low to medium density.
Type F	Road Mixed Traffic Public Network (Demand Driven)	<500	Bus, Taxi, Demand responsive (for example, e-hailing)	Low to medium density Mostly stops or e-hailing.

Rea Vaya commenced in 2009, starting with Phase 1A that includes a trunk route operating between Ellis Park in Doornfontein and Thokoza Park in Soweto, linking with several feeder routes in Soweto. Feeder buses run from Protea Glen to Thokoza Park and from Eldorado Park to Lakeview. The inner-city circular route travels around the Johannesburg CBD, from Hillbrow and Braamfontein to Ellis Park in the east and Chancellor House on the western edge of the city. Figure 4.11 shows the routes of Phase 1A and the areas that it covers. The Phase 1A trunk route has a length of 25 km and 27 stations. It was complemented by five feeder routes totalling 54 km and four complementary routes totalling 90 km.

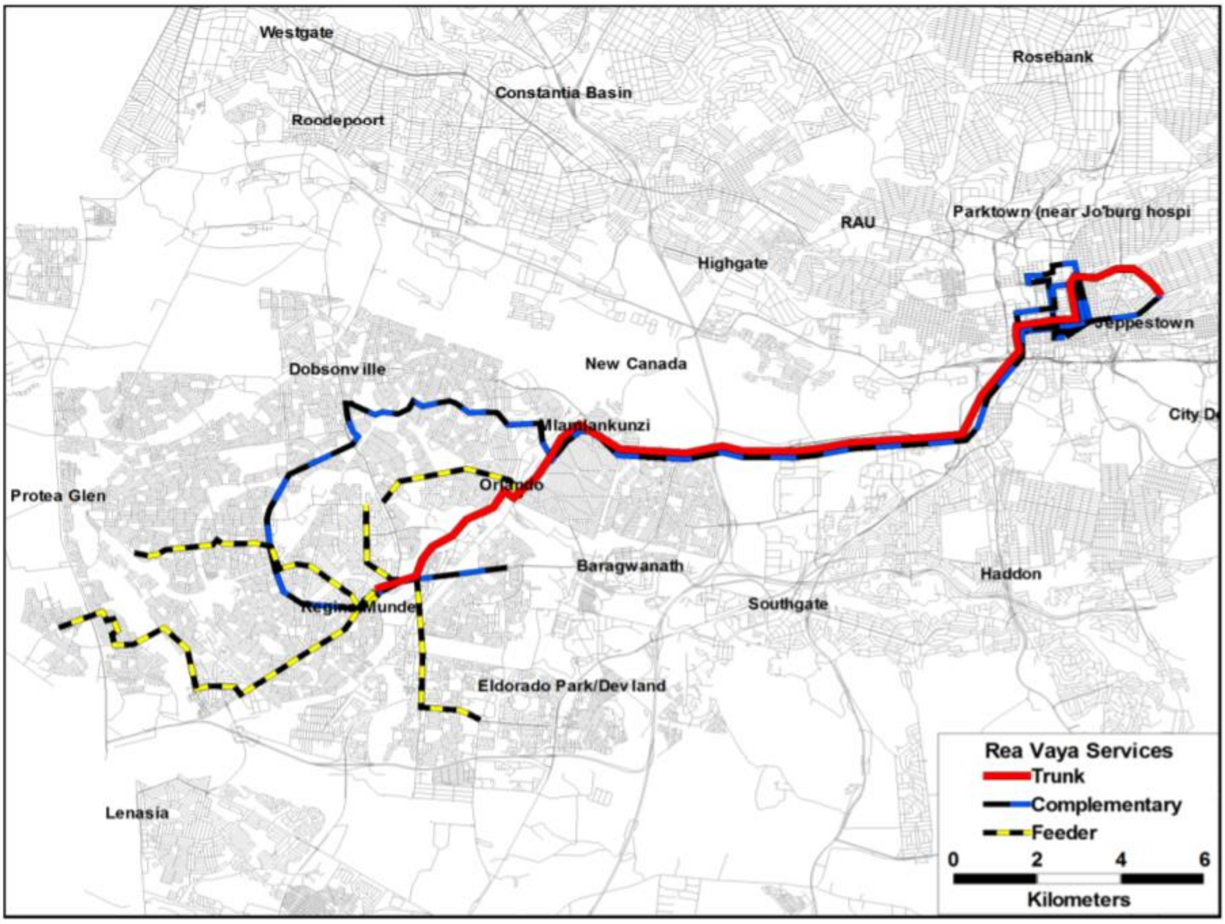


Figure 4:11 Rea Vaya Phase 1A route
(Source: McCaul and Ntuli, 2011)

Phase 1B of Rea Vaya services commenced in October 2013, with routes from Thokoza Park through Noordgesig Extension, Westbury, Auckland Park, Milpark, Parktown and to the Library Gardens in the Johannesburg CBD. The route starts in Noordgesig in Soweto and travels through Pennyville, New Canada, Highgate, Auckland Park and Braamfontein, to Parktown, Metro Centre and Rissik Street in the Johannesburg CBD. The route connects commuters to key public healthcare centres such as the Rahima Moosa, Helen Joseph and Charlotte Maxeke hospitals, and educational institutions such as the University of Johannesburg, Wits University, Milpark College, Parktown Boys' High School and Barnato Park High School. Feeder routes run to and from Leaglen, Stormhill, Florida, Cresta, Yeoville and Parktown. There are also additional feeders in Soweto from Pimville and Mapetla. The routes are linked to the Metro Centre Rea Vaya loop, which travels to the inner city via Braamfontein. Figure 4.12 shows a map of Phase 1A and 1B. The Phase 1B trunk route has a length of 18 km. It is complemented by 12 feeder routes totalling 62 km and six complementary routes totalling 82 km. Rea Vaya also has an express trunk route from Thokoza Park in Soweto to Braamfontein and operates only during the morning and afternoon peaks.

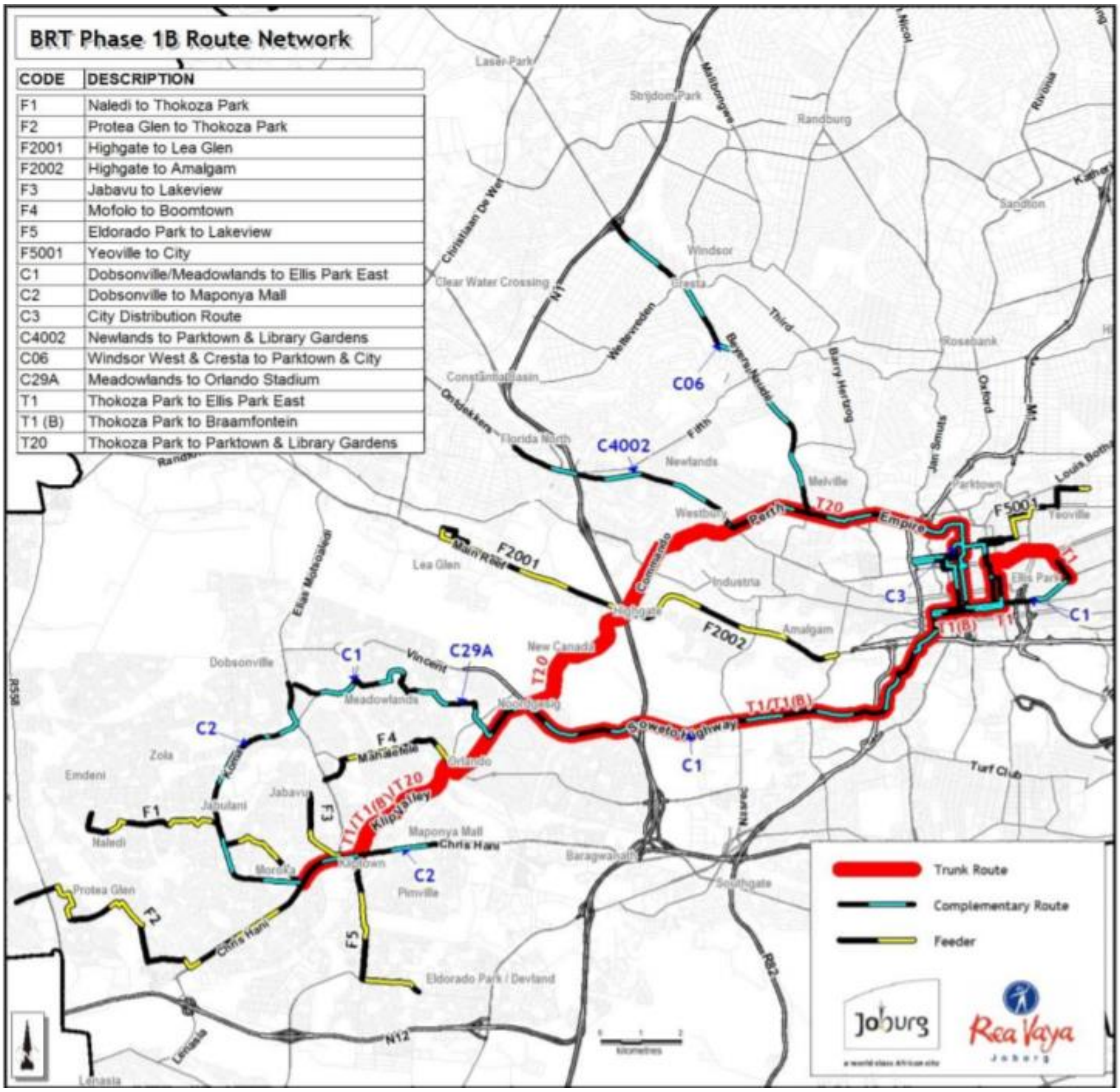


Figure 4:12 Rea Vaya Phase 1A and 1B
(Source: Standish et al., 2012)

Table 4.3 summarises the route characteristics of the 21 Rea Vaya routes with a specific focus on the route type, route length, area coverage and the number of trips per day.

Table 4.3 Rea Vaya route characteristics

Route name	Route type	Coverage	Route length (km)	Trips per direction per day
T1	Trunk	Thokoza Park to Ellis Park	25,8	153
T2	Trunk express	Thokoza Park to Constitution Hill	22,5	27
T3	Trunk	Thokoza Park to Library Gardens	23	139
C1	Complementary	Dobsonville to Ellis Park	24,5	122
C2	Complementary	Dobsonville to UJ Soweto	11,4	112
C3	Complementary	CBD to Library Gardens	11	60
C4	Complementary	Windsor to Library Gardens	16	81
C5	Complementary	Ontdekkers to Library Gardens	14,7	47
C6	Complementary	Meadowlands to Milpark Station	21	51
F1	Feeder	Naledi to Thokoza Park	7,3	124
F2	Feeder	Protea Glen to Thokoza Park	10,7	134
F3	Feeder	Jabavu to Lakeview	2,6	49
F4	Feeder	Boomtown to Mofolo	4,1	64
F5	Feeder	Lakeview to Eldorado Park	5,8	53
F6	Feeder	Fleurhof to Bosmont Station	6,6	70
F7	Feeder	Amalgam to Bosmont Station	7	52
F8	Feeder	Greymont to Westbury	5,3	49
F9	Feeder	Mapetla to Lakeview Station	4	67
F10	Feeder	Pimville to Lakeview Station	4	66
F11	Feeder	Yeoville to Library Gardens	6,6	65
F12	Feeder	Parktown distribution route	5,1	60

In terms of operation, the trunk, feeder, and complementary routes interact at the stations as they share docking bays to load and offload passengers and the trunk and complementary routes share the dedicated corridor in which both types of routes can operate. In terms of the vehicle capacities, trunk buses are articulated 18m units with a design capacity of 112 persons (seated and standing) with platform-level access, including room for disabled persons. Feeder and complementary buses have a design capacity of 81 passengers (seated and standing).

Figure 4.13 shows a trunk bus and a complementary/feeder bus.

Figure 4:13 Articulated trunk bus and standard feeder or complementary bus in the Rea Vaya system

In terms of the fare structure, the Rea Vaya fares are based on the journey distance. This structure is shown in detail in Table 4.4. The fares are paid using a smartcard, or passengers can purchase a single/double trip paper ticket at any Rea Vaya station. The smartcard costs R34.00, effective from 1 July 2020 to 30 June 2021. People travelling during off-peak hours (08:31–14:59) on Mondays to Fridays and any time on Saturdays, Sundays and public holidays are charged 10% less. For passengers who are transferring between buses, Rea Vaya has an automatic system transfer whereby passengers are not charged for a new trip when they change buses while in transit. However, where a passenger must change stations to connect, there is a 15-minute transfer window in which the system recognises the second trip as a continuation of the journey. This is the case for transfers at the following stations: iNdingilizi, Joburg Theatre, Carlton Centre, UJ Sophiatown, Library Gardens, and Chancellor House. If a passenger takes longer than 15 minutes to transfer, the journey will be counted as two separate trips, resulting in a higher cost per the rates in Table 4.4.

Table 4.4 Rea Vaya fares based on trip distance

Journey distance (km)	Fares (2020/2021) (R)
0–5	8,50
5,1–10	10,30
10,10–15	12,60
15,1–25	14,90
25,1–35	16,00
More than 35	17,10
Single trip card	22,00
Double trip card	42,00

Rea Vaya also has a points system that offers benefits to passengers. When commuters load cash onto their smartcards, they are charged a 2.5% transaction fee. A great benefit of the new points system is that there is no loading fee charged to load points onto the card; this is applicable when points are loaded at the Rea Vaya stations. Further, there are discounts offered in the form of top-up bonuses of between 5% and 12.5% (Table 4.5).

Table 4.5 Bonus system for Rea Vaya commuters

Money loaded onto card (R)	Percentage bonus (%)	Additional bonus value
10–50	0	0
51–100	5	From R2,60–R5,00
101–200	7	From R7,60–R15,00
201–300	10	From R20,10–R30,00
301–700	12,5	From R37,60–R87,50

The planning of the system was largely based on the ITDP's BRT Planning Guide, including the types of routes and fare system. Estimated passenger demand and route length were used to determine whether a dedicated lane was required as a trunk route. Since that time, the City of Johannesburg has developed an IPTN that consists of the following:

- a public transport network hierarchy;
- passenger access topologies;
- service design parameters;

- tools of integration across transport modes; and
- a long-term Strategic Integrated Public Transport Network (SIPTN) 2025 and 2037 Transport Sector Plan.

These components are collectively used as building blocks to develop detailed routes and service plans for the entire city.

Operationally, BRT implies rapid boarding and alighting, frequent services, short DTs, and average commercial speeds near the level of rail systems. BRT also presents a reforming of the public transport business model. Following the approval of Rea Vaya in 2006, the city embarked on consultations with the existing bus and informal minibus operators. The concept was to identify incumbent bus and minibus operators affected by the BRT system and negotiate the withdrawal of their vehicles and operating licences from potential BRT routes in exchange for participation as operators of the new system (McCaul & Ntuli, 2011). The deal enabled the incumbent operators to become shareholders of a bus operating company that signed a 12-year contract with the City of Johannesburg, thus benefitting more than 300 individual taxi owners (McCaul & Ntuli, 2011). From an employment perspective, displaced taxi drivers were also given employment opportunities in the new system. According to McCaul and Ntuli (2011), this agreement was a significant empowerment deal in the public transport sector in South Africa and transformative for both public transport operators and informal sector businesses.

The BRT system had to be planned in a constrained urban environment. In 2007, the City of Johannesburg approved a transport plan that set a target of having 85% of residents within one kilometre of a BRT trunk corridor or feeder route (City of Johannesburg, 2013). Customer surveys were conducted in 2011 and 2012 as part of the economic analysis for Phase 1A and 1B. There were in total 2100 usable surveys, but this represented a sample size of only 4% of the daily passenger numbers. The results showed that 75% and 76% could walk from origin to the first BRT stop and to destination from last BRT stop, respectively. Between 20% and 25% use other public transport services; feeder buses and 2% of users travel by private car.

Scorcia and Munoz-Raskin (2017) compared Rea Vaya to other BRTs in Latin America (see Figure 4.14). There were significant differences in average trip length and peak-to-base ratios, which were higher in Rea Vaya compared to Latin America, as well as the maximum load factors, which are lower in the Rea Vaya system.

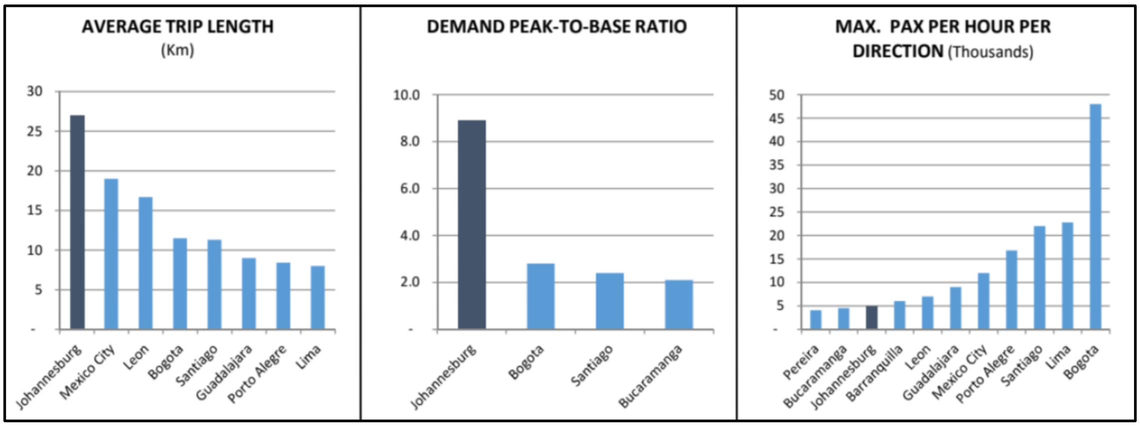


Figure 4:14 Comparing Rea Vaya to other countries using average trip length, demand peak-to-base ratio and maximum number of passengers

(Source: Scorcia & Munoz-Raskin, 2017)

Regarding waiting time, a user survey that was conducted in July 2012 indicated that about 80% of the users indicated that they do not have to wait longer than 15 minutes for their bus to arrive, with more than 50% saying that they wait no longer than 10 minutes (Figure 4.15).

Category	**July 2012 Survey % Users**
5 minutes	24%
10 minutes	30%
15 minutes	24%
20 minutes	11%
25 minutes	4%
30 minutes	5%
Longer	2%

Figure 4:15 Waiting time for Rea Vaya

(Source: Standish et al., 2012)

4.2. STATION SURVEYS

For this study, cordon surveys were conducted at five BRT stations for 12 hours from 06:00–18:00 on a typical weekday. These stations were chosen strategically based on their locations along the BRT corridor and station characteristics (Figure 4.16 indicates their location along the network).

In terms of location, they provide a snapshot of operations at various critical points along the network, especially at stations where T, F and C routes converge. They also cover a variety of operating environments.

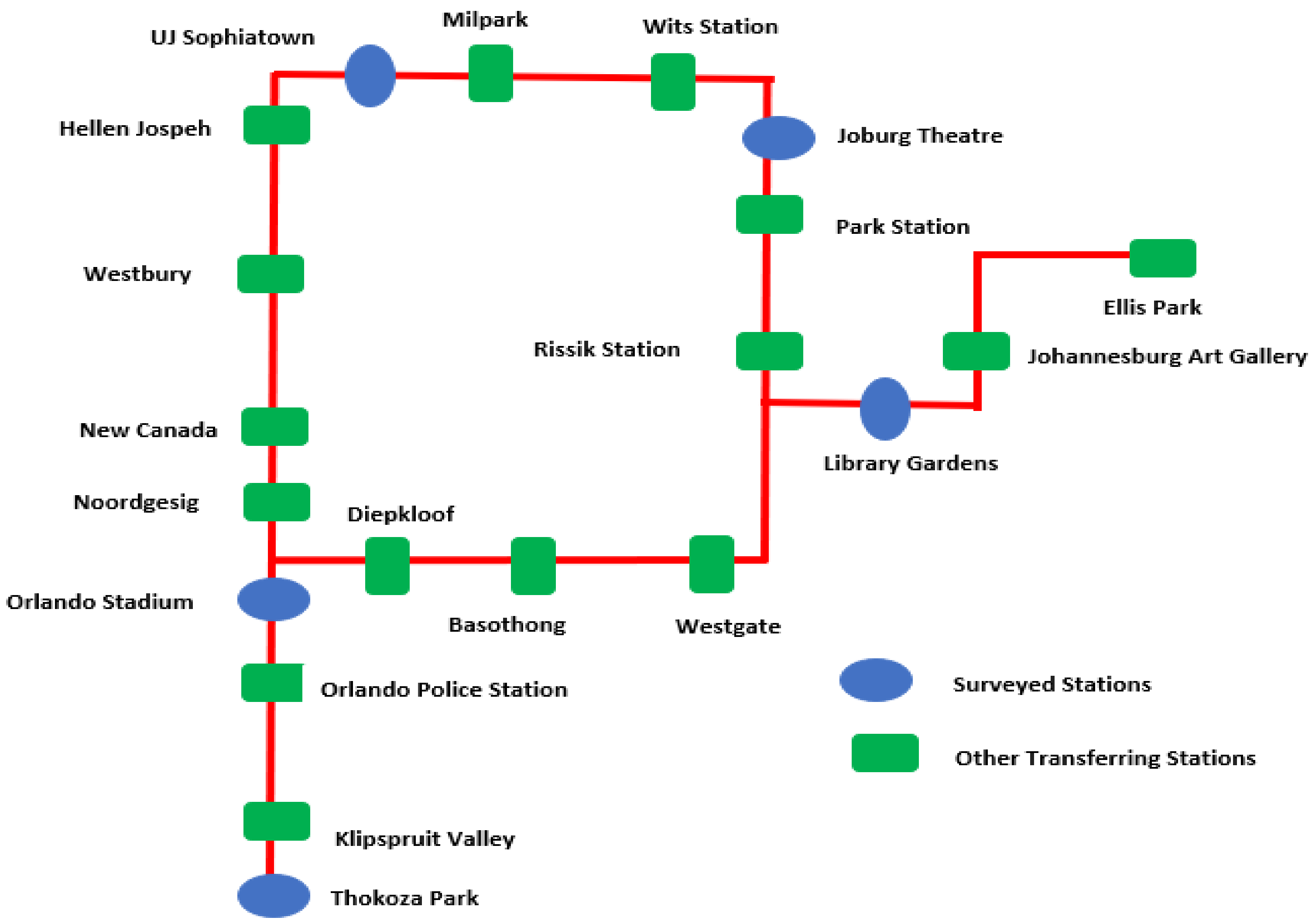


Figure 4:16 Rea Vaya route map showing the surveyed stations and the transferring stations

The five stations are Thokoza Park, Joburg Theatre, UJ Sophiatown, Orlando Stadium and The Library Gardens. Table 4.6 summarises the attributes of the stations.

The AM peak was observed between 06:00–09:00 and the PM peak between 15:00–18:00. The time in-between was considered off-peak.

Table 4.6 Attributes of the stations surveyed during the study

Station	Routes	Station type	Passing lane	Operating environment	Traffic direction
1. Thokoza Park	T1, T2, T3 F1, F2, F9 C2	In-station transfer	Yes	Suburban	Bi-directional
2. Joburg Theatre	T2, T3 F11, F12 C3, C4, C5	In-station transfer	Yes	Central business district	Unidirectional
3. UJ Sophiatown	T3 C4, C5, C6	Out-of-station transfer	Yes	Suburban	Bi-directional
4. Orlando Stadium	T1, T3 C1, C6	In-station transfer	Yes	Suburban	Bi-directional
5. Library Gardens	T1, T2, T3 F11, F12 C1, C3, C4, C5	Out-of-station transfer	Yes	Central business district	Unidirectional

1. Thokoza Park

Thokoza Park is a terminal station situated in Soweto; the trunk corridor starts at this station, and the complementary route (C2) enters the trunk corridor here. The station was surveyed on the 23 October 2018. The following routes were operational at the station: three trunk routes (T1, T2 [express route], T3), one complementary route (C2) and three feeder routes (F1, F2, F9). The three trunk routes were docking at the same bay. The complementary and three feeder routes were sharing one docking bay (Figure 4.17), which was the case for both east and west directions. Passengers from the feeder buses had a mandatory transfer from the feeder bus to either the trunk or the complementary bus, depending on the destination. The transfer was an 'in-station' transfer meaning there is no 'tap in' required at this station if the passenger is from a feeder bus and would tap out at their final destination unless their destination was Thokoza Park, in which case they would just tap out of the station.

A prominent feature around Thokoza Park Station is the green open space of Thokoza Park. The wider area consists of low-density residential dwellings.

Figure 4:17 Docking station for trunk, feeder, and complementary buses at Thokoza Park Station

(Source: Google Earth)

Figure 4.18 shows a plan view and the street view of Thokoza Park Station. The passing lane, and the side view of the station, can clearly be seen.

Figure 4:18 Thokoza Park BRT Station in Soweto
(Source: Google Earth)

2. Joburg Theatre

The Joburg Theatre BRT Station is situated in Braamfontein in the CBD adjacent to the municipal headquarters building. It is a transfer station. The station was surveyed on the 19 October 2018, and the following routes were captured: two trunk routes (T2, T3), three complementary routes (C3, C4, C5) and two feeder routes (F11, F12). The two trunk routes, three complementary routes and two feeder routes docked at the same bay (Figure 4.19). This station is located on a one-way street, so the buses move in a single direction. In terms of the operations, buses use the docking bay based on arrival, so it was a first come, first-served basis. If buses arrived one after the other, the bus that arrived first would dock while the others wait for their turn to dock. This station was also an 'in-station' transfer, and passengers would transfer from one bus to the other without requiring a 'tap in' at the station. Figure 4.20 depicts the plan and side view of the station.

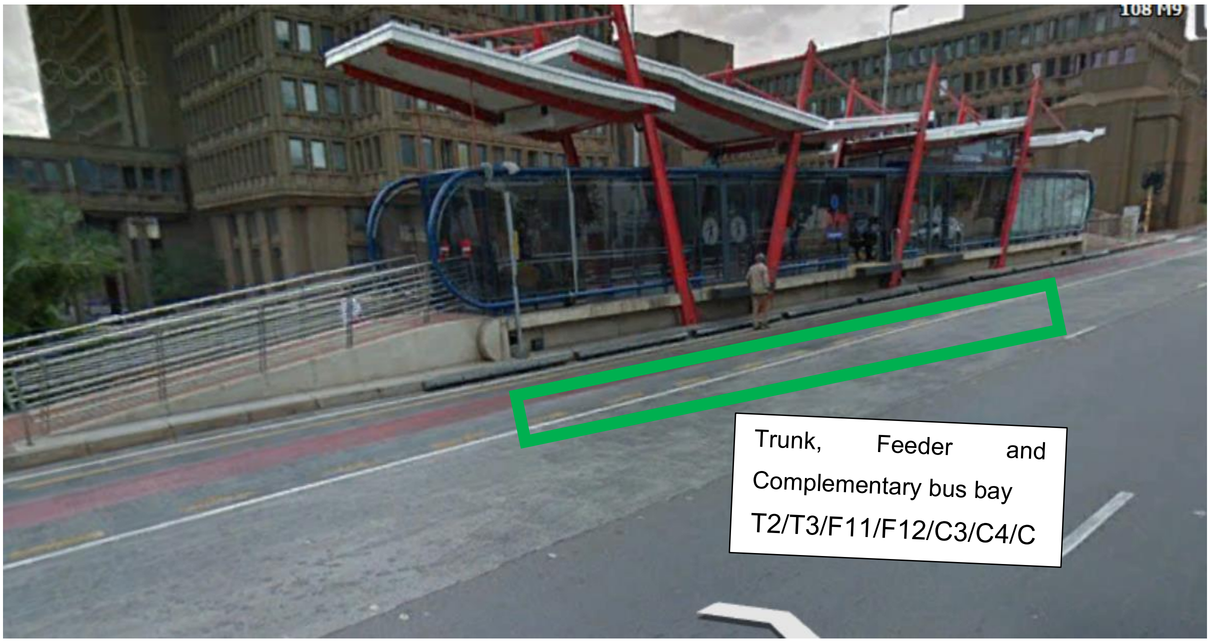


Figure 4:19 Space available for buses at the Joburg Theatre Station
(Source: Google Earth)

Figure 4:20 The Joburg Theatre BRT Station in Braamfontein
(Source: Google Earth)

3. UJ Sophiatown Residence

The station is situated in Auckland Park in a suburban environment next to a university campus. The complementary route C4 enters the trunk corridor at this station. This station was surveyed on the 3rd April 2019, and the following routes were captured: one trunk route (T3) and three complementary routes (C4, C5, C6). The trunk route and the three complementary routes docked here in the same bay (Figure 4.21); this was the case for the east and west directions. However, the east and west sections were separate (Figure 4.22) and passengers transferring from the east to west (or vice versa) have to tap out of one section, walk to the other section and tap in. There are no feeder buses at the station.

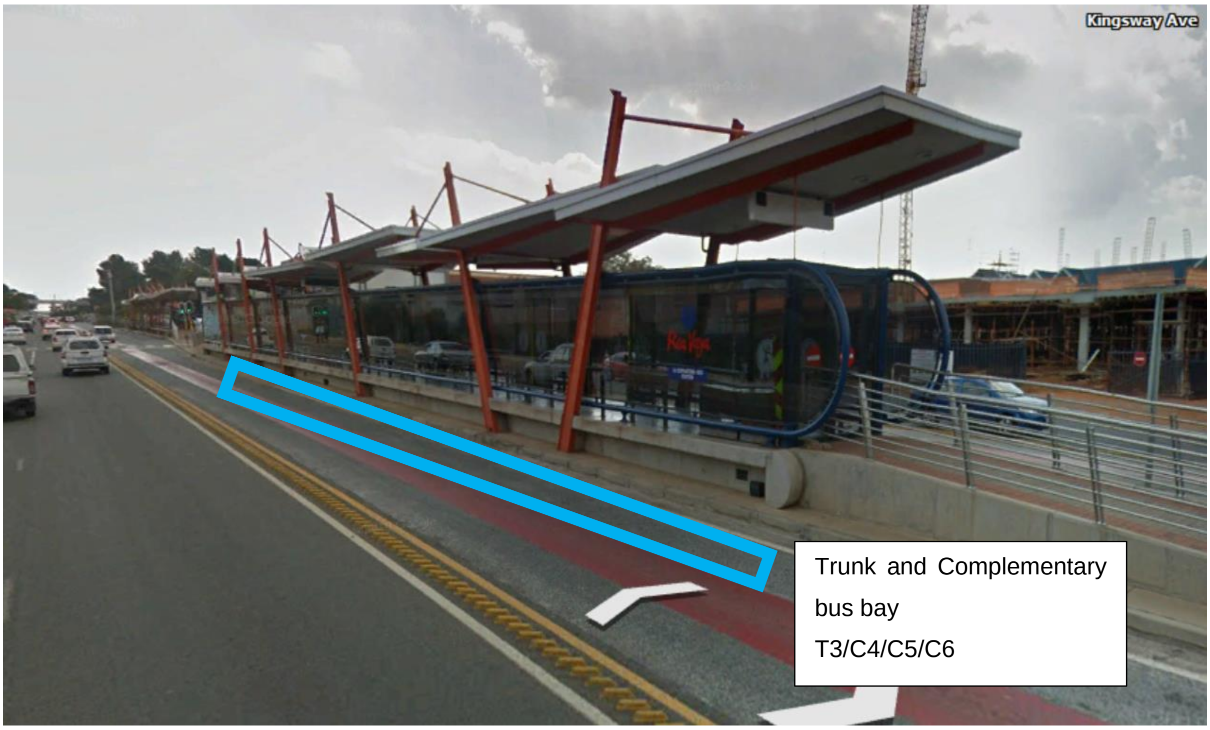


Figure 4:21 Space available for buses at UJ Sophiatown Station
(Source: Google Earth)

Figure 4:22 UJ Sophiatown Residence BRT Station in Auckland Park
(Source: Google Earth)

4. Orlando Stadium Station

This station is more like Thokoza Park in terms of configuration and is situated in Soweto. The complementary routes C1 and C6 enter the trunk network at this station. This station was surveyed on the 16 April 2019, and the following routes were captured: two trunk routes (T1, T3) and two complementary routes (C1, C6). The trunk route (T1) and complementary route (C1) share the same docking bay, whereas T3 and C6 also share a docking bay (Figure 4.23); this applies to both the eastbound and westbound direction. The station is an 'in-station' transfer. Passengers do not require to tap in and out if transferring from a trunk to a complementary route (or vice versa), depending on the destination. There are no feeder buses at the station. Figure 4.24 depicts the plan and side view of the station.

Figure 4:23 Space available for buses at Orlando Stadium Station

(Source: Google Earth)

Figure 4:24 Orlando Stadium BRT Station in Soweto

(Source: Google Earth)

5. Library Gardens

This station is situated in the heart of the Johannesburg CBD and has separate eastbound and westbound stations. The eastbound and westbound stations are located on different parallel one-way streets. Only the eastbound station was surveyed. This station was surveyed on the 4th April 2019, and the following routes were captured: three trunk routes (T1, T2, and T3), four complementary routes (C1, C3, C4, C5) and two feeder routes (F11, F12). The eastbound has two modules with T1, C1, C4 and C5 sharing a docking bay and T2, T3, C3, F11 and F12 also sharing a docking bay (Figure 4.25). Transferring passengers must tap out of one module, walk to the other module, and tap in, depending on the destination. The feeder buses feed into the trunk and complementary routes.

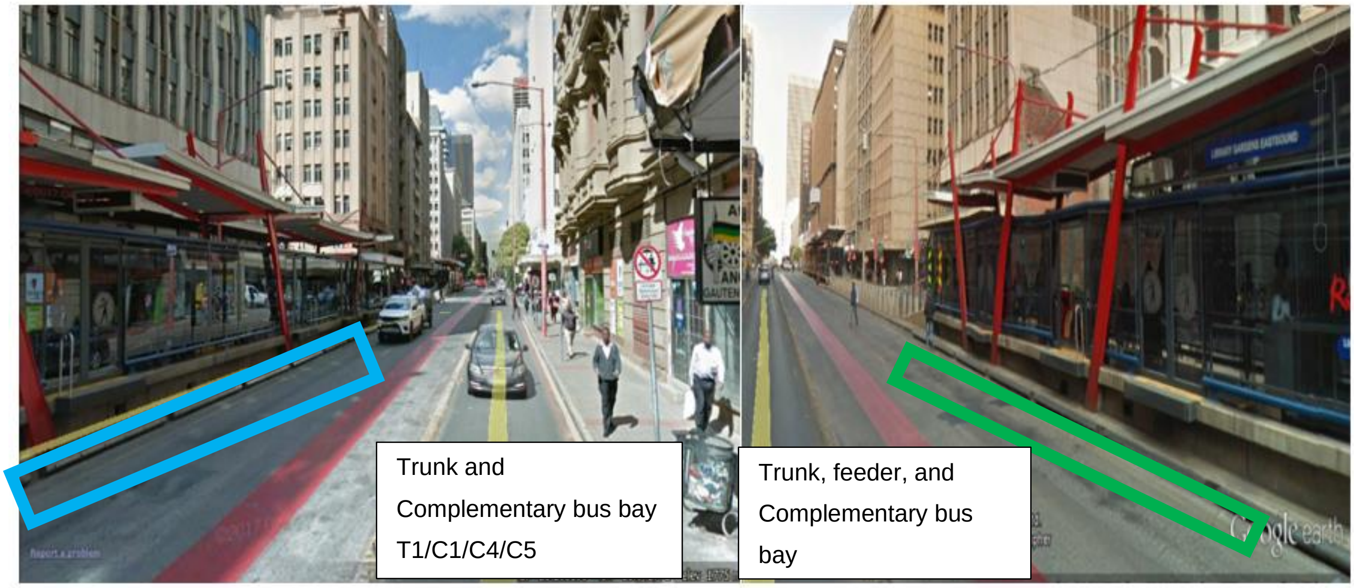


Figure 4:25 Library Gardens East BRT Station in Johannesburg CBD
(Source: Google Earth)

As mentioned, cordon surveys were conducted for a 12-hour shift and surveyors were positioned inside the station. A survey form was created and used by the surveyors on site (Appendix D).

The following information was captured, as summarised in Table 4.7:

- bus arrival times
- bus route type
- docking time at the station
- bus delays

- number of passengers boarding

Table 4.7 Summary of information captured during the station surveys

Data Captured during the survey	Methodology
Bus arrival times	Recorded the time that each bus arrived at the station
Bus route type	Recorded the bus route type (trunk/feeder/complementary) when the bus arrived. Each bus has the route type branded on the bus
Docking time	Recorded the time elapsed between when the bus doors opened to the time the doors closed to allow for boarding's and alighting's using a stopwatch
Bus delay	Recorded the time elapsed between when the bus was at the station and the time it docked, using a stopwatch. This was usually the time when it was waiting for another bus to finish docking and clear the lane
Number of passengers boarding	Counted the number of passengers boarding each bus at the station

Bus GPS data would have been ideal for capturing the docking and delay times and would have given more accurate data. However, this data could not be obtained from the City of Johannesburg.

4.3. ON-BOARD SURVEY

In 2016 the city of Johannesburg embarked on a high-level operational analysis of the Rea Vaya BRT system to better understand the operational performance and find solutions to reduce the operational cost deficit. Data was collected to aid the analysis that included two types of survey (on-board and cordon) on all 21 routes for three weeks (1^{st} to 21^{st} February 2016). The on-board surveys captured the actual cycle times, the number of boarding and alighting per stop/station and passenger occupancy.

The operational characteristics and key performance indicators (as of April 2016) of the Rea Vaya can be seen in Table 4.8. The cost per passenger is higher than the revenue per passenger, indicating a deficit (in this case, a subsidy is required). According to Bulman and Valjarevic (2016), the operating costs per kilometre are higher than two other cities (referred to as City A and C in the report). The revenue cost ratio of 34% is low, and the aim is to increase it to above 40%; this can be achieved by increasing the peak fares and reducing direct operating costs (Bulman & Valjarevic, 2016).

Table 4.8 Operational characteristics and key performance indicators of Rea Vaya (April 2016)

No. of peak buses (excl. spares)	247
No of drivers	396
No. of average weekly boarding passengers	60 312
No. of monthly boarding passengers	1 355 184
Monthly operational kilometres	969 965
Monthly fare income	R11 081 413
Direct monthly operating cost (excluding station management)	R32 233 551
Monthly operating profit/deficit	R-21 152 138
Revenue per passenger	R8,18
Operating deficit per passenger	-R15,61
Operating cost per passenger	R23,79
Revenue cost ratio	34%
Operating cost per kilometre	R33,23
Driver ratio	1.6

4.4. TICKETING INFORMATION

The City of Johannesburg has provided a full set of passenger ticketing data for September 2017 for Phases 1A and 1B. The month of September was chosen as typical in the sense that there were no service interruptions. The ticketing data was supplemented by route data, consisting of all the serviced routes, stations and stops.

All passenger entries or exits into and out of the Rea Vaya system are supposed to generate a ticketing transaction when a smart card is used. Cards are swiped on entry to the first station (if on the trunk) or bus (if off-trunk) and swiped again on exit. Figure 4.26 shows the entry point at Joubert Park Station.

Figure 4:26 Entry and exit point at Joubert Park Station

The format of the supplied ticketing data is shown in Appendix E.

The data entries include:

- the date and time when the card transaction occurred;
- the card number, which is unique for each passenger and allows matching of entry and exit of a passenger;
- the type of transaction (check-in, check-out, or failure) (last column); and
- the station or stop boarding (or alighting station) number and name where the transaction occurred.

However, the ticketing data contained card errors and needed to be cleaned to obtain a usable sample of data. In some cases, the boarding or alighting errors are due to insufficient funds on the card. It is a requirement that there must be a minimum of R17 on the smartcard to travel. It is not known what actions the passenger took after being refused entry to the system. In some

cases, a card reading failure caused the entry refusal, as the cards were successfully swiped again a few seconds later.
The total check-in and check-out card errors (including insufficient funds) make up 8% of all the card readings in September 2017. Of these, insufficient funds make up most refusals. These transactions were removed from the dataset before further analysis. There are other anomalies in the data; for example, some passengers only have their boarding or alighting transactions registered and, hence, have one leg of their trip missing from the data. These were also removed. Other errors include passengers with exceptionally high journey times. A maximum of two hours was used to cap the journey times. Anything more was considered an outlier and was removed.
From the ticketing data, the following information is extracted for this analysis:

- The trip duration is computed from the difference between the boarding and alighting time. From this, an average passenger trip time matrix (on an O-D basis) is constructed using MATLAB[3] as a tool.
- The total number of boardings and alighting's at a station or stop.
- The O-D matrix per route number and route type. This allocation of trips to routes is not entirely accurate because certain sections on the trunk network are serviced by both trunk and complementary routes. This is not a problem when a given O-D pair is uniquely served by only one route. In the case of two or more routes, a rules-based approach is developed to determine the most likely route taken. For all trips within the trunk network, it was assumed that a trunk bus was boarded even though in some sections served by both trunk and complementary buses, passengers had an option to board bus type, depending on which bus arrived first. This assumption was deemed to be reasonable because of the high frequencies of the trunk buses.
- By matching the O-D matrix with a distance table, passenger-kilometres can be determined from the data, per route number and route type. By matching the distance table with the trip time matrix, average passenger travel speeds are calculated per route type.

4.5. SYSTEM DATA

Operator data is sourced from the system on operating costs (including maintenance costs, insurance, for example) for the bus operations only.

The operating cost model is based on the following input parameters:

---

[3] MATLAB is a programming tool.

Route details

- an average of 21 weekdays
- total route length per month to be calculated using the equation:

$$Route\ length * number\ of\ trips\ per\ day * numberof\ days\ per\ month$$

Bus costs

- fuel consumption of 62 litres/100 km for an articulated bus and 55 litres /100 km for a standard bus;
- vehicle comprehensive insurance at a premium of 4.5% of capital costs per annum;
- diesel price of R16.5 per litre as of November 2019;
- maintenance cost of R14,66 per km for articulated buses and R11,91 per km for rigid buses;
- tyre cost of R0,59 per km for articulated buses and R0,52 per km for rigid buses; and
- vehicle licence at R26 000 per year for articulated buses and R22 000 per year for rigid buses.

Driver costs

- three driver shifts on a weekday and two shifts on the weekend;
- driver rate (escalated at 6% per annum from R6465 in 2013); and
- the model also caters for driver uniform and training (escalated at 10% per annum from a standard rate of R80 and R90 respectively per driver in 2013).

The bus schedules with bus-kilometres and bus capacity numbers, and stop locations were also sourced from the operator.

4.6. CHARACTERISTICS OF DATA COLLECTED

From the data collected from the station surveys, as explained in Section 4.2, some deductions can be made concerning the observations. Sometimes it was not possible to start the data capturing at 6:00 precisely because of the notifications that had to be sent to the control centre before starting the surveys (which was not always on time). For this study, the trunk and feeder routes represent the trunk-feeder network, and the complementary routes represent the direct network.

4.6.1 Number of buses

The number of buses arriving was observed at Thokoza Park and depicted in Figure 4.27. The number of buses for the trunk-feeder network is higher than those of the direct network; this is the case for various times of the day. This was because the number of routes that represent the trunk-feeder network was more than the routes representing the direct network (three [3] trunk routes, three [3] feeder routes and one [1] complementary route). The AM peak was between 07:00-08:00, and the PM peak was between 16:00-17:00 for both the trunk-feeder and direct networks.

For Thokoza Park, the trunk-feeder network reaches a maximum of 60 buses per hour, and the direct network reaches a maximum of just over ten buses per hour.

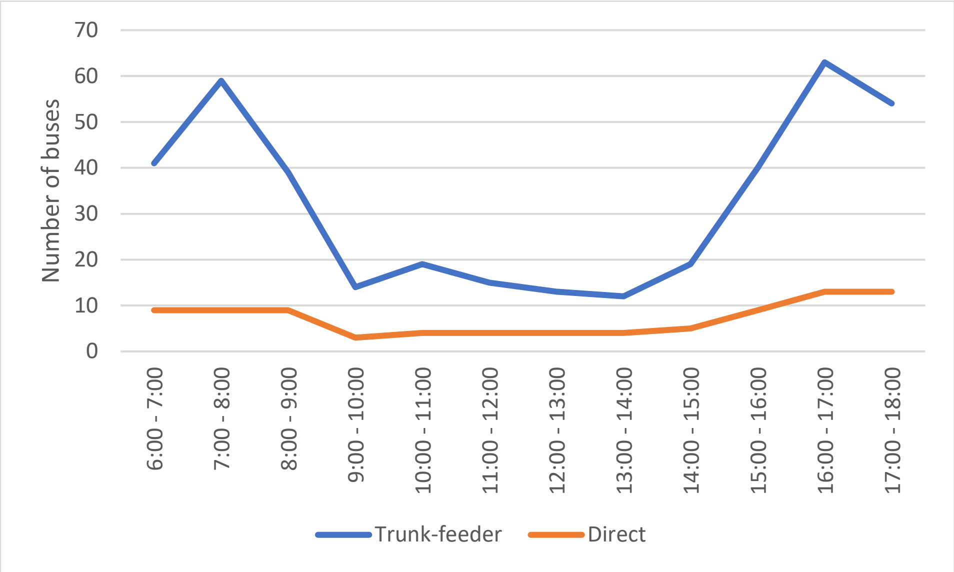


Figure 4:27 Number of buses at Thokoza Park Station on an hourly basis

At the Joburg Theatre Station, the number of buses per hour for the direct versus trunk-feeder networks can be seen in Figure 4.28. At this station, the number of buses for the trunk-feeder network is not always higher than that of the direct network, as seen at Thokoza Park. The number of buses for the direct network is higher than that of the trunk-feeder network between 08:00–10:00 only, which could be attributed to the different headways applied across the routes at various times. What has also been observed at this station was that for the direct network, the AM peak was later (08:00–09:00), and the PM peak was earlier at 15:00. This could be due to the location of the station and buses whose routes start far from the station (Cresta C4 route, for example) take too long to get there. For the Joburg Theatre Station, the trunk-feeder network reaches a maximum of about 20 buses per hour, and the direct network reaches a maximum of 15 buses per hour.

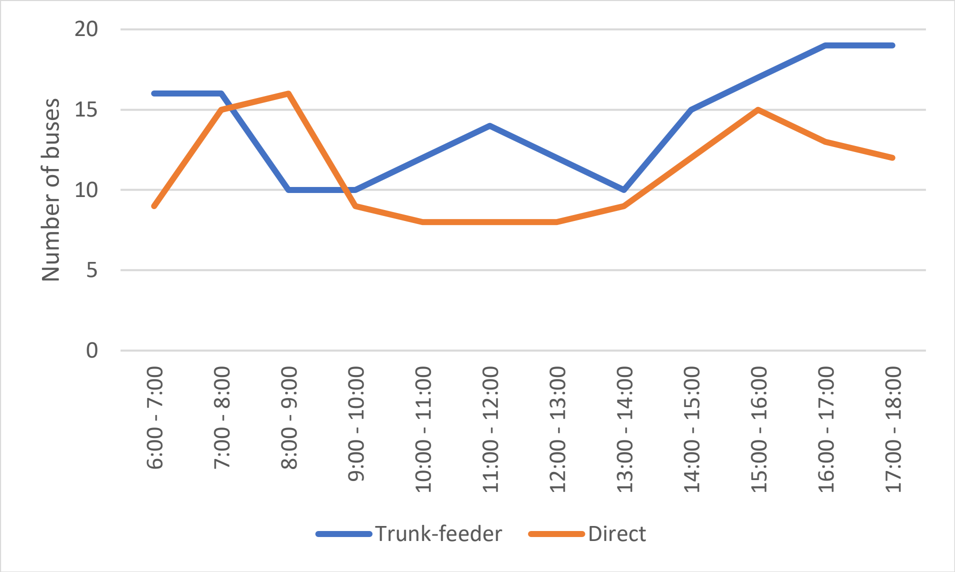


Figure 4:28 Number of buses at the Joburg Theatre Station on an hourly basis

At the Orlando Stadium Station, the number of buses per hour for the direct versus trunk-feeder networks can be seen in Figure 4.29. At this station, the number of buses for the direct network is not always higher than that of the trunk-feeder network, as seen at Thokoza Park. Also, there was no PM peak: this could be due to the missed (or cancelled) trips. The number of buses for the direct and trunk-feeder networks was quite similar and consistent at this station, with there being two trunk routes and two complementary routes being serviced at this station. For Orlando Stadium, the trunk-feeder network reaches a maximum of 22 buses per hour, and the direct network reaches a maximum of 24 buses per hour.

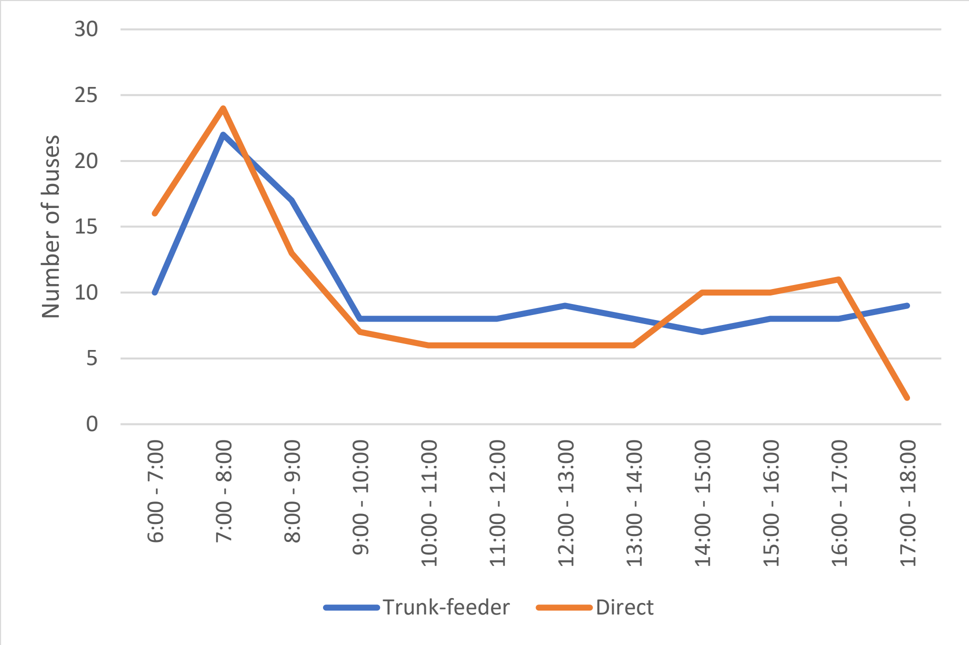


Figure 4:29 Number of buses per hour at Orlando Stadium

At the Library Gardens Station, the number of buses per hour for the direct versus trunk-feeder networks can be seen in Figure 4.30. This station had the highest number of buses compared to the other four stations, which is also consistent with there being more routes (nine) serviced at this station compared to the other four stations. The AM peak at this station is later than the other four stations (08:00–09:00 compared to 07:00–08:00 observed at the other stations), which is due to the station being in a highly trafficked CBD area and buses being subjected to high levels of congestion and delays on the road. The station is located towards the end of the route, so buses take a long time to get there. The buses for the trunk-feeder network are more than those of the direct network. This is the case for various times of the day, due to the higher number of routes that represent the trunk-feeder network (five) compared to those that represent the direct network (four).

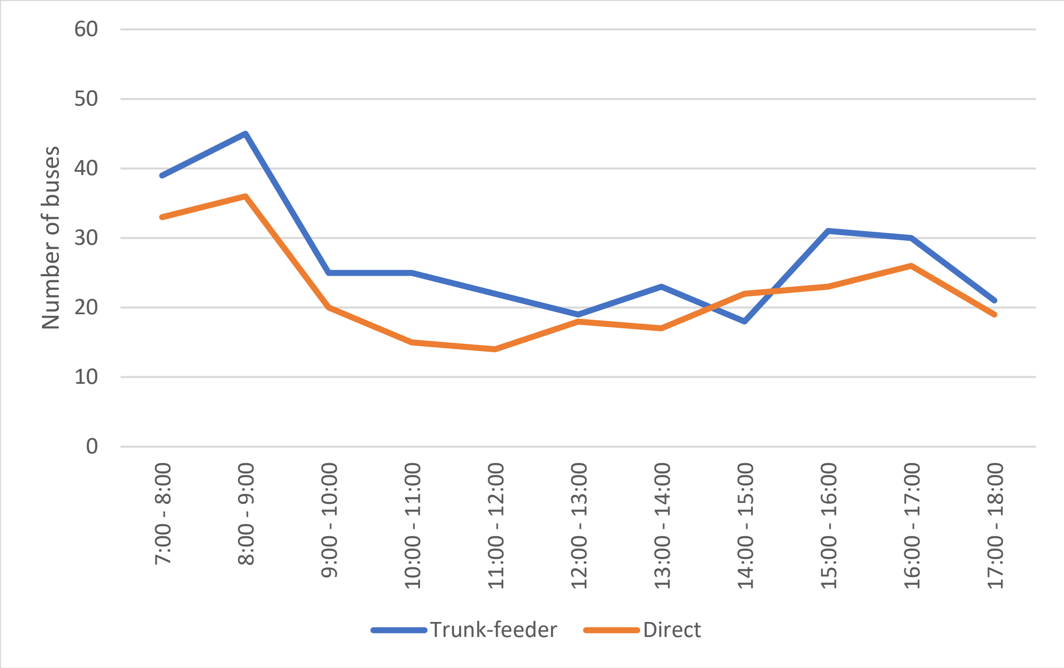


Figure 4:30 Number of buses per hour at Library Gardens

For UJ Sophiatown, similar trends were observed as those already discussed. The number of buses per hour is shown in Appendix B.

4.6.2 Scheduled headways

The scheduled headways for the different routes varied throughout the day and varied amongst the different routes. Figure 4.31 shows the headways for the different routes at Thokoza Park. The longest headway during the peak period was 10 minutes and 30 minutes during the off-peak period. The trunk routes had the shortest headways (high frequencies), followed by the complementary routes, with the feeder routes having the longest headway (low frequencies). It was also observed that the changes in headways occurred at different times for the different routes. For example, for the C2 route, the headway increases after 08:00 (less frequent) and decreases after 14:00 (more frequent), which could be attributed to the route servicing students going to the UJ Soweto campus and it being aligned to travel times for students.

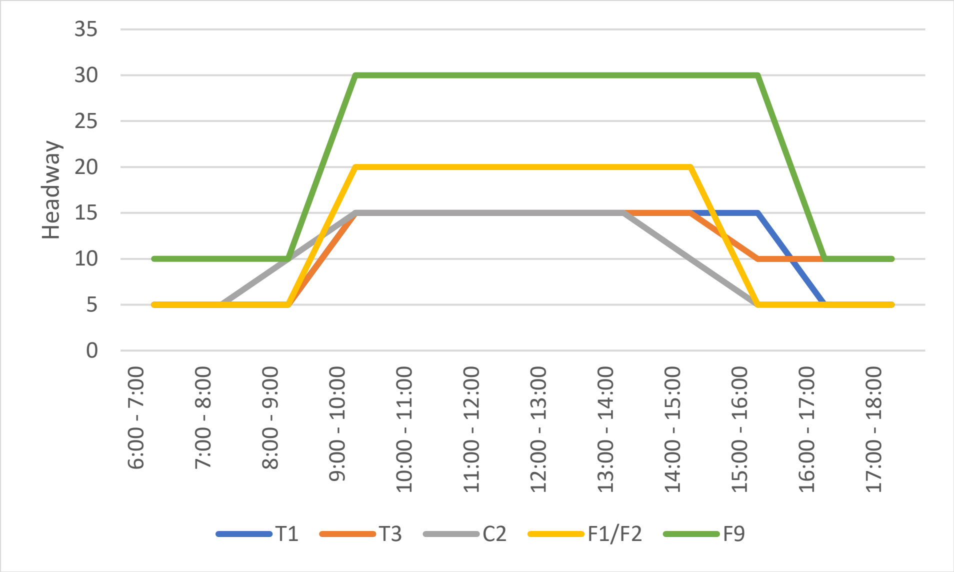


Figure 4:31 Scheduled headway at the Thokoza Park Station

For the Joburg Theatre Station, the headways for the different routes are shown in Figure 4.32. The longest headway at this station is 15 minutes during the peak period and 30 minutes for the off-peak period. The C5 route has the longest headway (less frequent) compared to the other routes (this is the case across the day), which could be due to the low demand on the route.

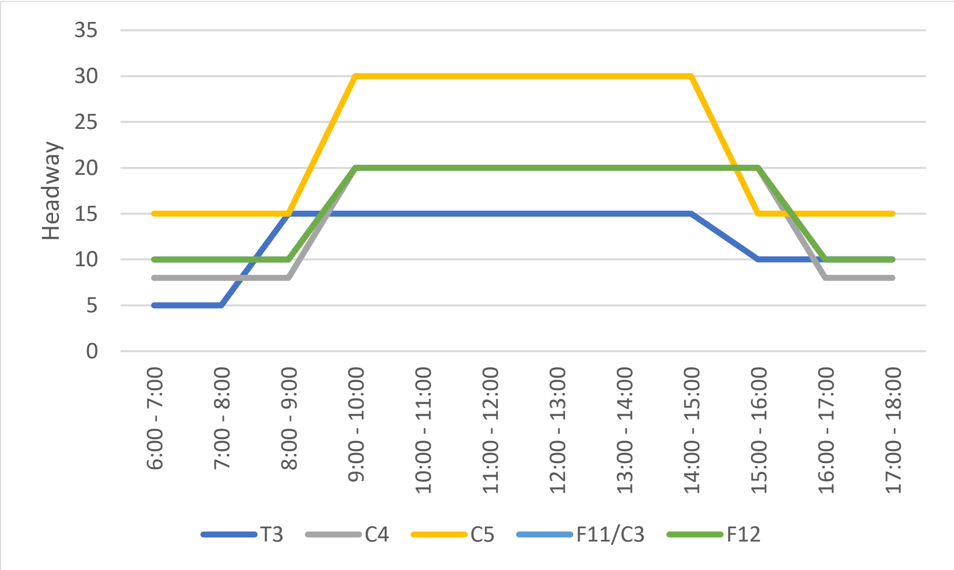


Figure 4:32 Scheduled headway at the Joburg Theatre Station

The scheduled headway for the routes at UJ Sophiatown is depicted in Figure 4.33. At this station, the headway for the C4 route was different compared to the other routes (AM peak was longer and PM peak was shorter). This is consistent with the high volumes of passengers observed during the AM peak and not in the PM peak. Also, the trunk routes are more frequent than the complementary routes.

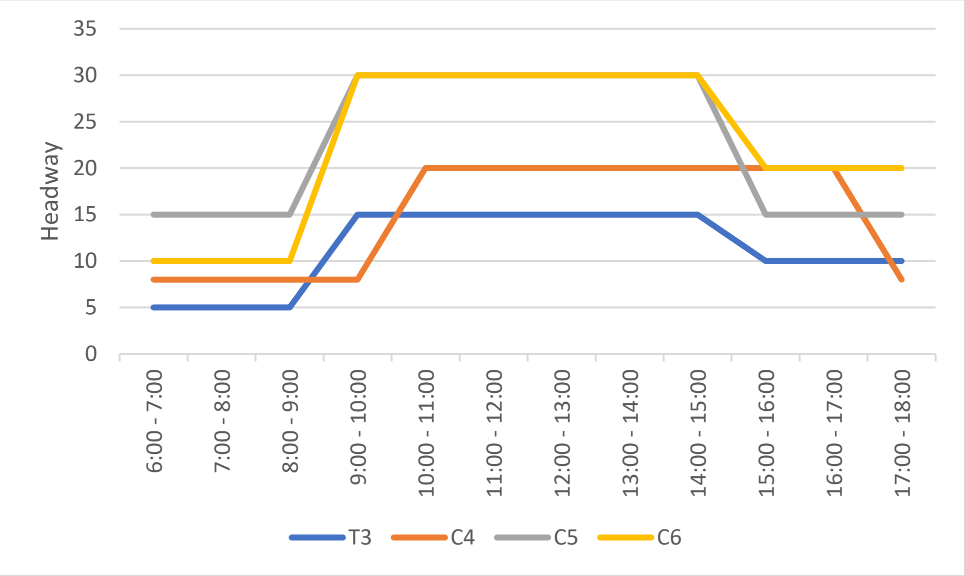


Figure 4:33 Scheduled headway at UJ Sophiatown Station

The scheduled headway for the routes at Orlando Stadium is shown in Figure 4.34. At this station, the trunk routes and C1 route have the same headway across the day, except that the C1 route has an extended off-peak headway. This is consistent with the decrease in passenger numbers using this route after 08:00. From the station observations, the number of passengers boarding the C1 was an average of 181 passengers per hour before 08:00 and then declined drastically to 35 passengers per hour after 08:00 until 18:00m.

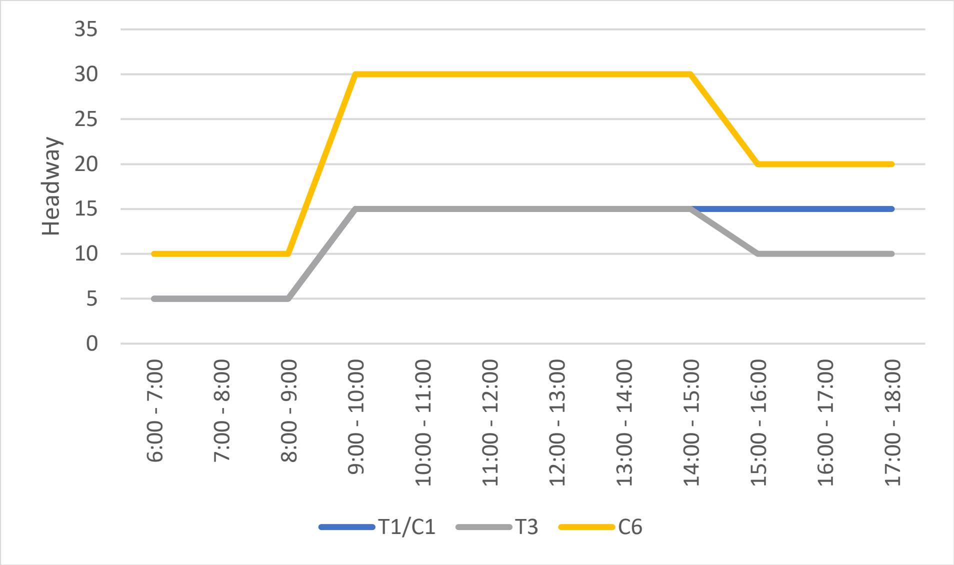


Figure 4:34 Scheduled headway at Orlando Stadium Station

Figure 4.35 shows the scheduled headway for the routes at the Library Gardens Station. As with the other stations, the headway varies across the different routes and across the day. The trunk routes and the feeder routes have the shortest headways and are very frequent, followed by the complementary routes.

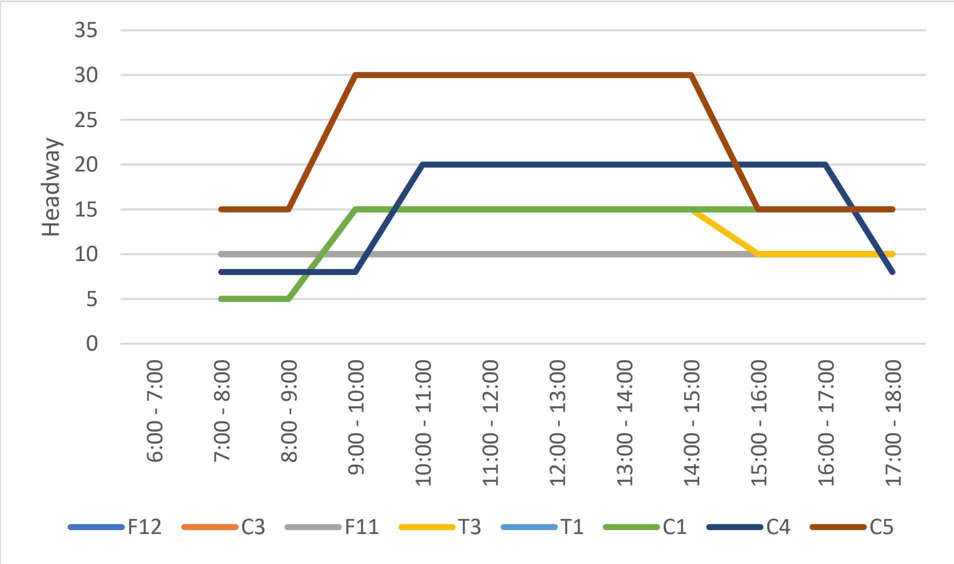


Figure 4:35 Scheduled headway at The Library Gardens Station

4.6.3 Demand

The ticketing data was used to determine the number of boardings and alightings for the entire system, as explained in the previous sections. The AM peak hour was between 06:30–07:30, and the PM peak between 16:00–17:00 (See Figure 4.36 for this and the demand variation across the day.)

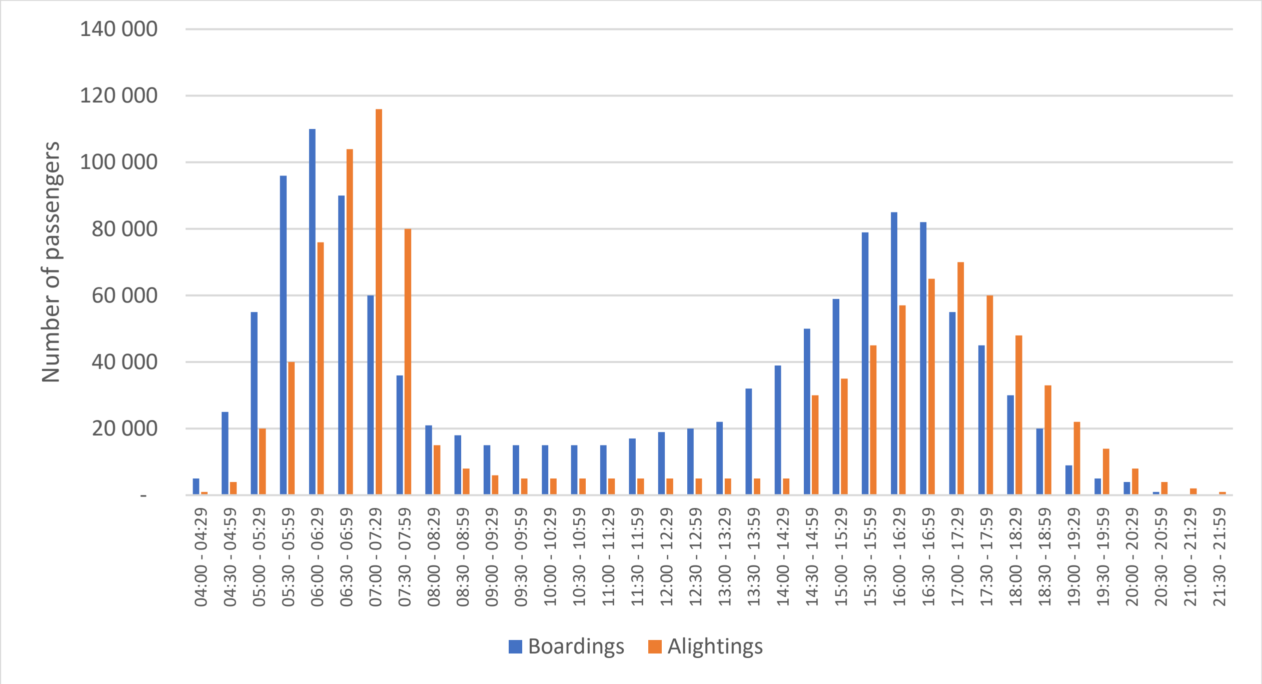


Figure 4:36 All-day demand profile for Rea Vaya

From the origin and destination matrix, the number of boardings and alighting's per station was deduced. Thokoza Park, Library Gardens and Park Station were the busiest stations for passenger boardings and alighting's (Figure 4.37).

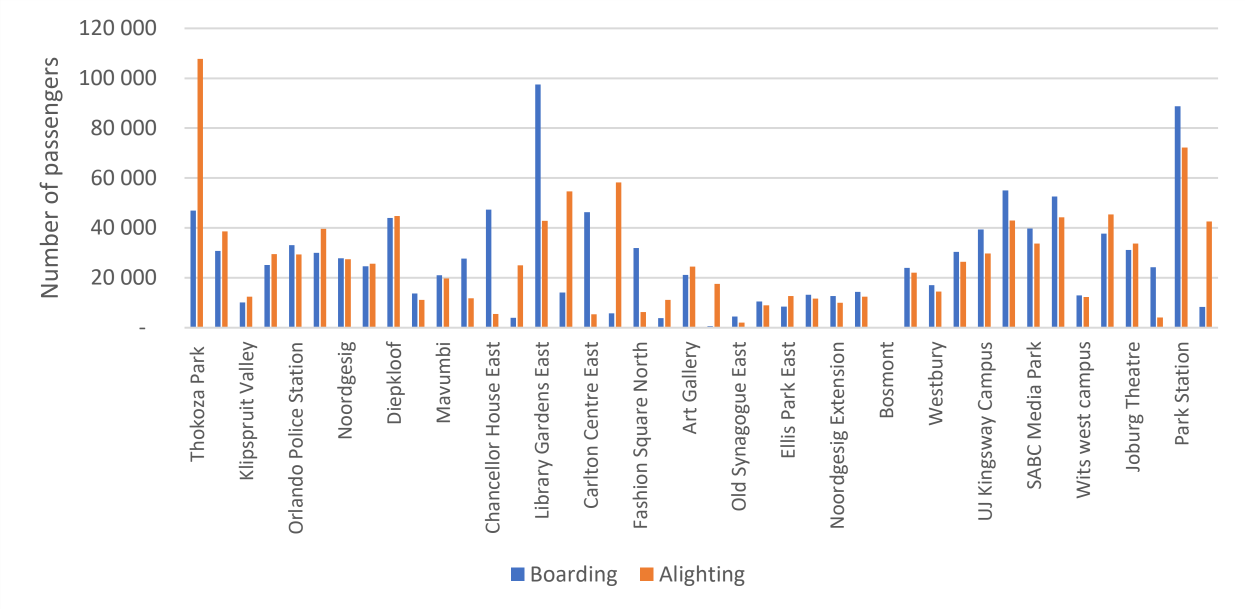


Figure 4:37 Total daily demand per station

From the on-board surveys, the maximum numbers of passengers per hour per direction using the different routes were recorded and graphically represented in Figure 4.38. The two trunk routes (T1 and T3) were the busiest, with 2508 and 2401 passengers per hour per direction, respectively. The express route (T2) had 719 passengers per hour per direction. This route was only operated during peak periods and only stopped at a few stations along the trunk corridor. Concerning the complementary routes, the C1 had 1052 passengers per hour per direction, which was the highest. F2 had 1273 passengers per hour per direction, which was the highest of all the feeder routes.

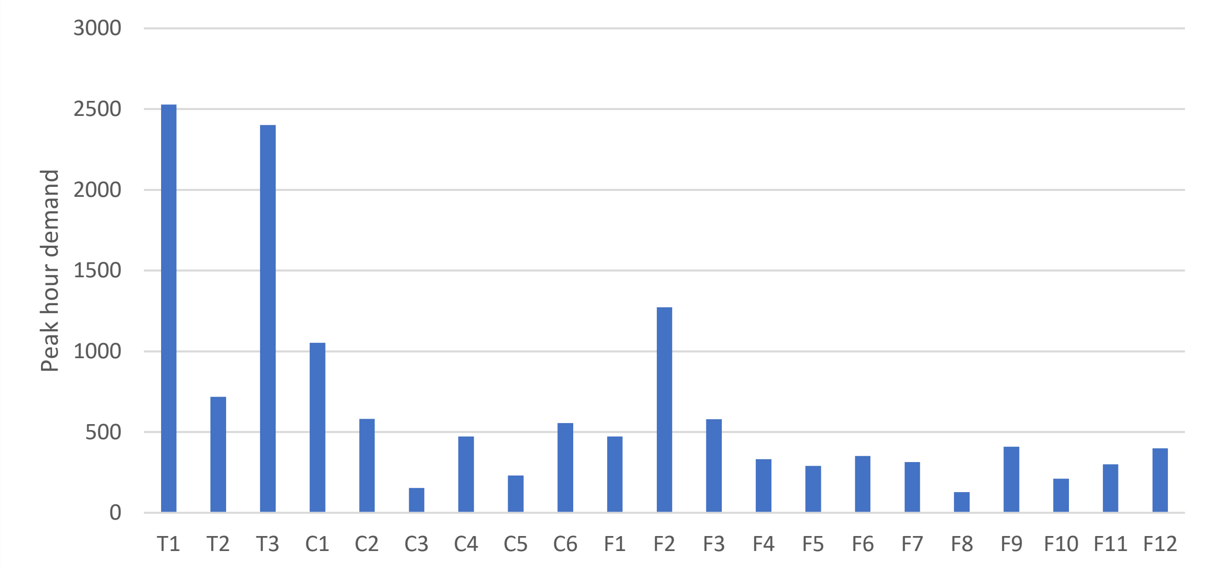


Figure 4:38 Peak hour demand per route

4.6.4 Discussion

Based on the results that were collected, several deductions can be made about the Rea Vaya system. The three route types (trunk, feeder and complementary) generally vary in the system in terms of function and performance. The frequencies were discussed in the previous section, and the frequencies were different for the AM peak, PM peak and off-peak: this is the case for all route types. This was done to align with the demand patterns that were observed to be different across the day (see Figure 4.36). The trunk buses carry higher passenger volumes than the complementary and feeder routes. The trunk buses fulfil the function of bulk transportation by using 18m articulated buses and high frequencies. The complementary and feeder buses carry medium to low passenger numbers using standard 12m buses. According to the City of Johannesburg modal hierarchy developed as part of the IPTN, the function of the complementary buses was to improve system coverage using frequent services. The function of the feeder buses was to increase catchment areas and connect passengers from low-density areas to the trunk and complementary routes. However, according to the current operations and results obtained, there is no clear modal hierarchy on complementary and feeder routes. For example, the complementary and feeder buses are similar in terms of the demand, vehicle size and, in some instances, frequency as well (see previous sections). The only clear differences observed are the land use along which the two route types operate and the route length (complementary routes are longer than feeder routes). Complementary routes also operate predominantly in mixed-use densified areas, whereas the feeder routes operate on low to medium density residential areas.

5 RESULTS AND DISCUSSION

The approach of this research was explained in Chapter 3. A set of hypotheses was formulated based on the issues identified and the literature collected. This chapter aims to test the hypotheses and discuss the findings. Statistical testing is used to aid in the analysis. The following indicators are measured according to make comparisons and recommendations about direct versus trunk-feeder BRT:

- headway reliability;
- station saturation;
- speed;
- load factor; and
- operating costs.

The findings will be contextualised in the case of Rea Vaya BRT and the City of Johannesburg, where the system is being operated, giving an opportunity to explore the local issues further.

For the purposes of this study, the trunk-feeder network is represented by the trunk and feeder routes and the direct network is represented by the complementary routes. Also, the AM peak period is between 06:00–09:00, the PM peak period is between 15:00–18:00, and the off-peak period is between 09:00–15:00.

5.1. HEADWAY RELIABILITY

The headway irregularity index was calculated for the direct and trunk-feeder BRT networks for the five BRT stations surveyed. This was done on an hourly basis throughout the day (Figures 5.1 to 5.5). The headway irregularity index measures the reliability of the actual headways against the scheduled headway. It is expected to be high in the direct BRT network because it operates in mixed traffic, is subjected to congestion and other delays on the road and only enters the dedicated trunk network at specific locations. The trunk-feeder is expected to have a lower headway irregularity index because the trunk buses operate in a controlled environment on dedicated trunk networks.

For Thokoza Park, the headway irregularity index for the trunk-feeder network was the highest during the morning peak between 08:00–09:00, and in the afternoon peak between 15:00–16:00, reaching 1,6 and 1,7, respectively. The headway irregularity is higher in the peak period than the off-peak period. Regarding the direct network, the headway irregularity index reached highs of 1 and 0,6 in the AM (07:00–08:00) and PM (16:00–17:00) peak periods. Also, the headway irregularity index for the AM peak was higher than that of the PM peak. As with the trunk-feeder network, the off-peak headway irregularity index is lower than that of the peak periods.

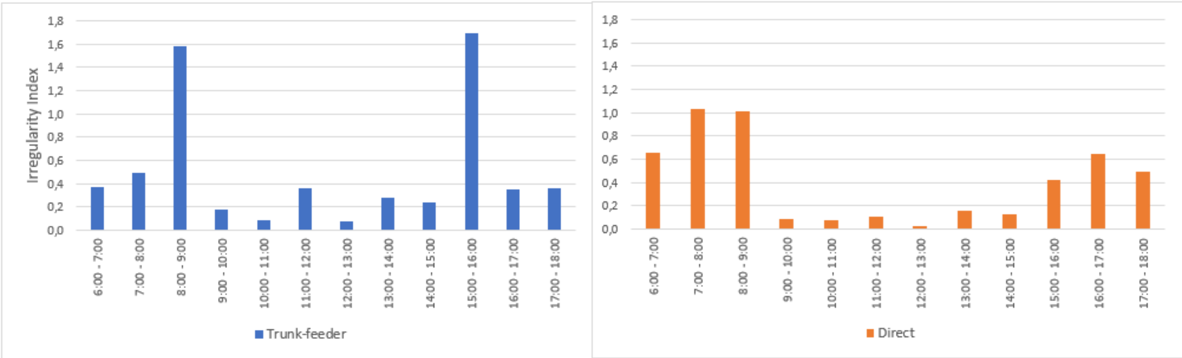


Figure 5:1 Headway irregularity index for trunk-feeder and direct BRT at Thokoza Park Station

For the Joburg Theatre Station, the headway irregularity index for the trunk-feeder network reached highs of 1 and 2 in the AM (08:00–09:00) and PM (17:00–18:00) peaks. The overall headway irregularity index for the off-peak period is lower than that of the peak period. The direct network also reached highs of 1 and 1,2 in the AM (08:00–09:00) and PM (17:00 to 18:00) peaks, respectively. The off-peak headway irregularity index is lower than that of the peak periods.

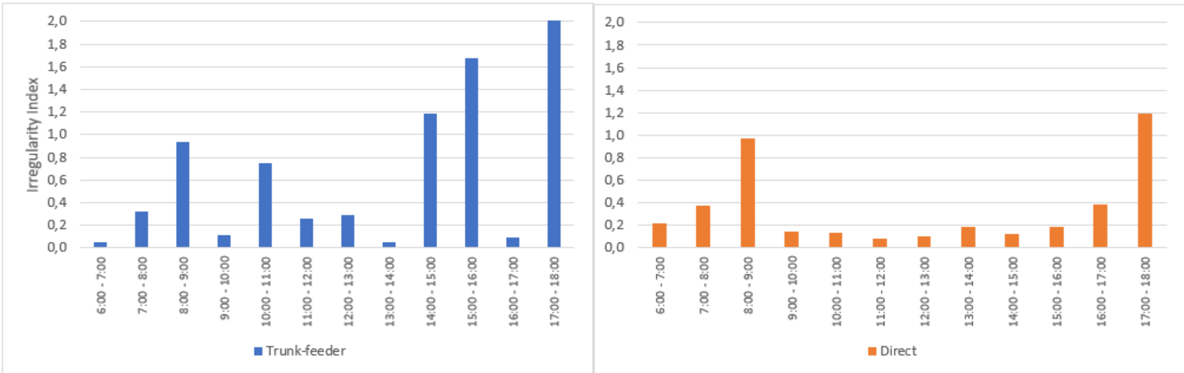


Figure 5:2 Headway irregularity index for trunk-feeder and direct BRT at the Joburg Theatre Station

At UJ Sophiatown, the headway irregularity index for the trunk-feeder network reached highs of 0.5 and 1.2 in the AM (08:00–09:00) and PM (17:00–18:00) peaks, respectively. The headway irregularity is higher in peak periods compared to the off-peak periods. The direct network reached highs of 0.5 in the AM peak (08:00–09:00) and 0.2 in the PM peak (17:00–18:00). The headway irregularity index in the peak period is higher compared to the off-peak period.

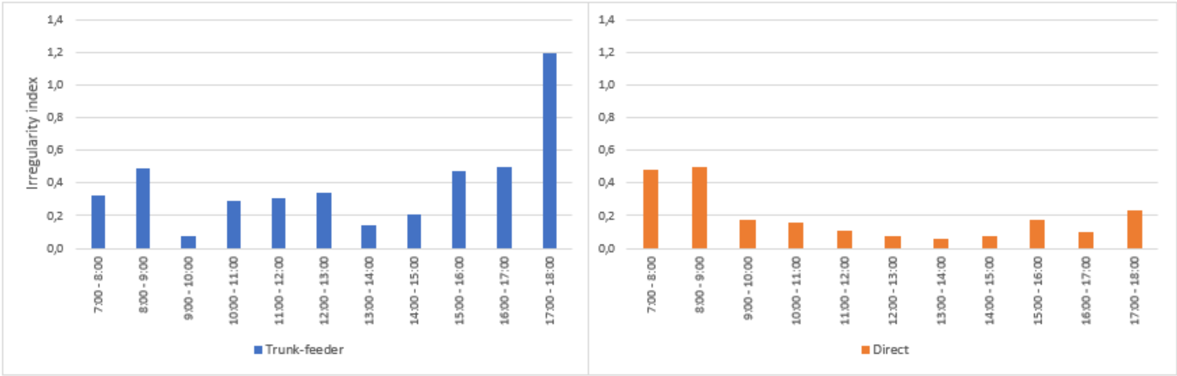


Figure 5:3 Headway irregularity index for trunk-feeder and direct BRT at UJ Sophiatown Station

For the Orlando Stadium Station, the headway irregularity index for the trunk-feeder network reached highs of 1 and 0.5 respectively in the AM (08:00–09:00) and PM (17:00–18:00) peaks, respectively. The direct network reached highs of 0.4 and 0.1 in the AM (08:00–09:00) and PM (16:00–17:00) peaks, respectively. The off-peak headway irregularity index is lower than that of the peak for both the trunk-feeder and direct networks.

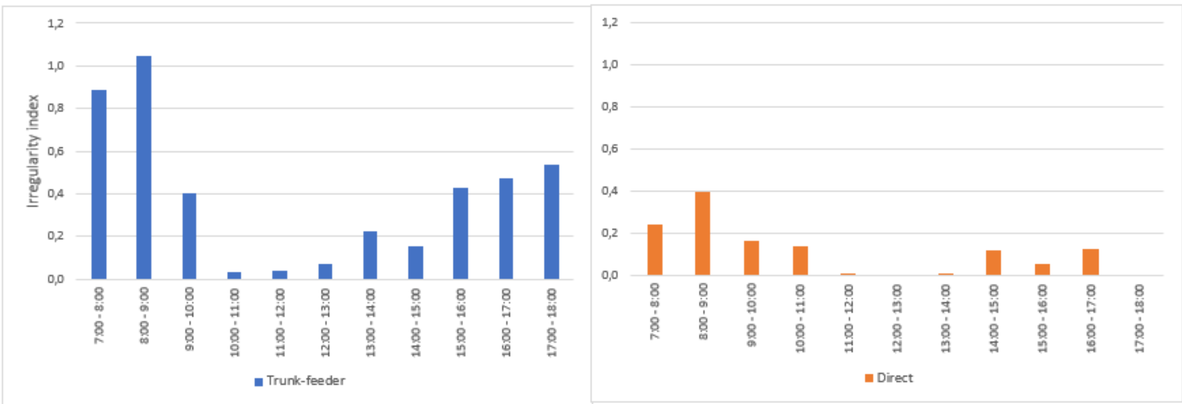


Figure 5:4 Headway irregularity index for trunk-feeder and direct BRT at Orlando Stadium Station

At the Library Gardens Station, the headway irregularity index for the trunk-feeder network reached highs of 0.5 in the AM peak (08:00–09:00) and 0.6 during off-peak (13:00–14:00) and PM peak (15:00–16:00). The direct network reached highs of 0.7 in both the off-peak (09:00–10:00) and PM peak (17:00–18:00). At this station, the off-peak headway irregularity index is higher than that of the AM peak period.

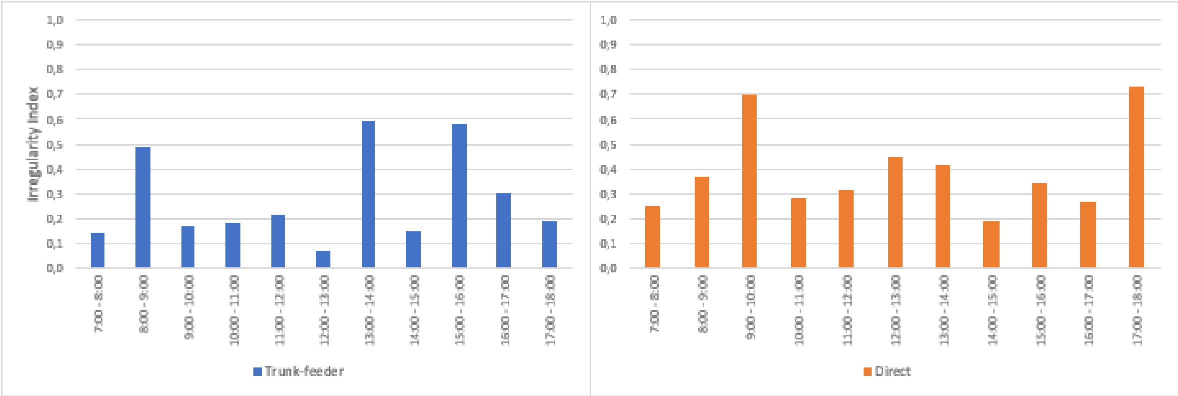


Figure 5:5 Headway irregularity index for trunk-feeder and direct BRT at the Library Gardens Station

From the results, the headway irregularity index for both trunk-feeder and direct BRT networks varies by time of day; this is the case for all the stations that were surveyed. There is a clear distinction between the headway irregularity index in the peak periods and the off-peak periods, with high irregularities observed during the peak periods. First, the scheduled headways are different between peak and off-peak periods, resulting in more buses operating during peak times compared to off-peak times. Second, the peak-to-base ratio in Johannesburg is high and, according to Scorcia and Munoz-Raskin (2017), it is calculated to be nine. This means that there is a high demand during peak times and low demand during off-peak: this was also observed during the station survey. The stations were almost empty during off-peak. Lastly, the traffic conditions are different for peak and off-peak periods. High levels of congestion were observed during the peak times.

Table 5.1 is a summary of the results for different parts of the day for the five surveyed stations.

Table 5.1 Summary of headway irregularity index for AM peak, PM peak, off-peak and all day at the different stations

	AM peak		Off-peak		PM peak		All day	
	Trunk-feeder	**Direct**	**Trunk-feeder**	**Direct**	**Trunk-feeder**	**Direct**	**Trunk-feeder**	**Direct**
Thokoza Park	1,04	1,02	0,2	0,1	0,8	0,52	0,52	0,38
Joburg Theatre	0,63	0,68	0,44	0,13	1,4	0,59	0,74	0,35
UJ Sophiatown	0,41	0,49	0,23	0,11	0,72	0,17	0,4	0,19
Orlando Stadium	0,97	0,32	0,15	0,08	0,48	0,06	0,39	0,12
Library Gardens	0,31	0,31	0,23	0,39	0,36	0,45	0,28	0,39

A statistical t-test was used for hypothesis testing to compare the headway irregularity index for the trunk-feeder and direct networks. There are three main types of t-test:

- Independent Samples t-test that compares the means for two groups;
- Paired sample t-test that compares means from the same group at different times (say, one year apart); and
- One sample t-test tests the mean of a single group against a known mean.

For this study, a two-sample independent t-test is used. One-tail is deemed suitable because there is an expectation that the irregularity for the direct network is more than that of the trunk-feeder network.

The null hypothesis for the independent sample t-test is $Irr_{T\_F} >= Irr_{Direct,}$ and the alternative hypothesis is that $Irr_{T\text{-}F} < Irr_{Direct}$

For this analysis, the data was separated in terms of the time of day (AM peak, off-peak, and PM peak), which was done to account for the time-of-day variations observed from previous chapters or even from the data collected. Also, the stations are grouped into two based on similarity in operations. Group 1 comprises Thokoza Park, Joburg Theatre, and the Library Gardens; these stations are combined because they service all three route types (trunk, feeder and complementary). Group 2 comprises UJ Sophiatown and Orlando Stadium, and these stations are combined because they service only two types of routes (trunk and complementary).

For the t-test, the applicable sample size (n) is <=25 for both samples.

For Group 1, the results are shown in Table 5.2 and are summarised as follows:

For the AM peak period, the p-value is more than 0,05, so the null hypothesis is accepted. For the off-peak period, the p-value is more than 0,05, so the null hypothesis is accepted. For the PM peak period, the p-value is more than 0,05, so the null hypothesis is accepted.

Table 5.2 Statistical t-test results for Group 1

t-Test: Two-Sample Assuming Unequal Variances						
	AM peak		*Off-peak*		*PM peak*	
	Trunk-feeder	*Direct*	*Trunk-feeder*	*Direct*	*Trunk-feeder*	*Direct*
Mean	0,67	0,66	0,29	0,20	0,85	0,51
Variance	0,27	0,13	0,08	0,02	0,71	0,09
t Stat	-0,04		1,08		1,10	
P(T<=t) one-tail	0,48		0,14		0,14	
t Critical one-tail	1,83		1,70		1,81	

For Group 2, the results are as shown in Table 5.3. For the AM peak, off-peak, and PM peak periods, the p-value is more than 0,05, so the null hypothesis is accepted.

Table 5.3 Statistical t-test results for Group 2

t-Test: Two-Sample Assuming Unequal Variances						
	AM peak		*Off-peak*		*PM peak*	
	Trunk-feeder	*Direct*	*Trunk-feeder*	*Direct*	*Trunk-feeder*	*Direct*
Mean	0,68	0,40	0,19	0,12	0,55	0,14
Variance	0,11	0,01	0,01	0,001	0,03	0,002
t Stat	1,58		1,6		1,56	
P(T<=t) one-tail	0,09		0,06		0,11	
t Critical one-tail	2,13		1,76		1,94	

For Group 1, the null hypothesis was accepted for AM peak, off-peak, and PM peak, meaning that the irregularity for the trunk-feeder network is more than that of the direct network. For Group 2, the null hypothesis was accepted for the AM peak, off-peak, and PM peak, which means that the headway irregularity index for the trunk-feeder network is more than that of the direct network.

When the operations at the operations are closely inspected, UJ Sophiatown and Orlando Stadium (Group 2) have less complex operations in the sense that both stations only service four routes (made up of trunk and complementary routes only), the delays are minimal, and not much interference was observed. Regarding stations in Group 1 (Thokoza Park, Joburg Theatre and Library Gardens), the operations are complex, servicing seven or more routes made up of trunk, complementary and feeder routes. These complexities are consistent with the observations during the surveys where buses were all arriving simultaneously, competing for the docking bay and delaying each other. This is due to the first come, first-served approach applied where no buses were given priority when docking at the station. Although the trunk buses are operated on the dedicated network, there is no priority given at the stations.

During the station surveys, it was observed that the dedicated lane was used by minibus taxis and private vehicles, causing significant delays on the trunk network. Urgent law enforcement is required to eliminate this problem. The traffic signals not operating regularly also caused major delays on the trunk network. Load shedding has negative implications on the functionality of traffic signals. Load shedding, or planned electricity outages, is done countrywide in South Africa as a controlled option to respond to unplanned events, protecting the electricity power system from a total blackout. The dedicated lane, in this case, does not fully realise the benefits of exclusivity with less/no congestion. Figure 5.6 shows the extent of the lawlessness of drivers along the BRT dedicated lane.

Figure 5:6 Other motorists encroaching on the dedicated BRT lane

Figure 5.7 shows the extent of bus bunching observed at the Library Gardens Station, where four buses arrived at the same time. Bus bunching is when buses running along the same corridor, scheduled to be evenly spaced, run with highly variable headways instead. The frequency of this occurrence has a direct impact on schedule adherence. Buses arriving in a very small (bus bunching) or very large headway influence bus service performance (Lin & Ruan, 2008).

Figure 5:7 Bus bunching at the Library Gardens Station

The delay of the buses at the stations, primarily due to bunching, was recorded. Delays are captured to reflect the incidence of buses having to wait for another bus to dock. The operations are such that different buses share a docking bay, and the combinations include a trunk bus delaying another trunk or a feeder or a complementary bus and vice versa.

At Thokoza Park Station, there are two bays per direction, one for the trunk buses and one for the complementary and feeder buses. During the peak period, buses were all arriving at the station simultaneously, resulting in delays because there are only two bays available for use. Buses must wait until the bus that has arrived first has completed docking. At Thokoza Park Station, it was also noted that the DT (time from which the doors open, passengers board and alight until the doors close) for buses was long, with trunk buses averaging 94 seconds, complementary buses with an average of 40 seconds and feeders with an average of 46 seconds. These high DTs can also be attributed to the high passenger numbers that were seen transferring from trunk bus to the feeder buses or vice versa. Figure 5.8 shows the extent to which the station was highly trafficked, and the delays experienced during the peak hour.

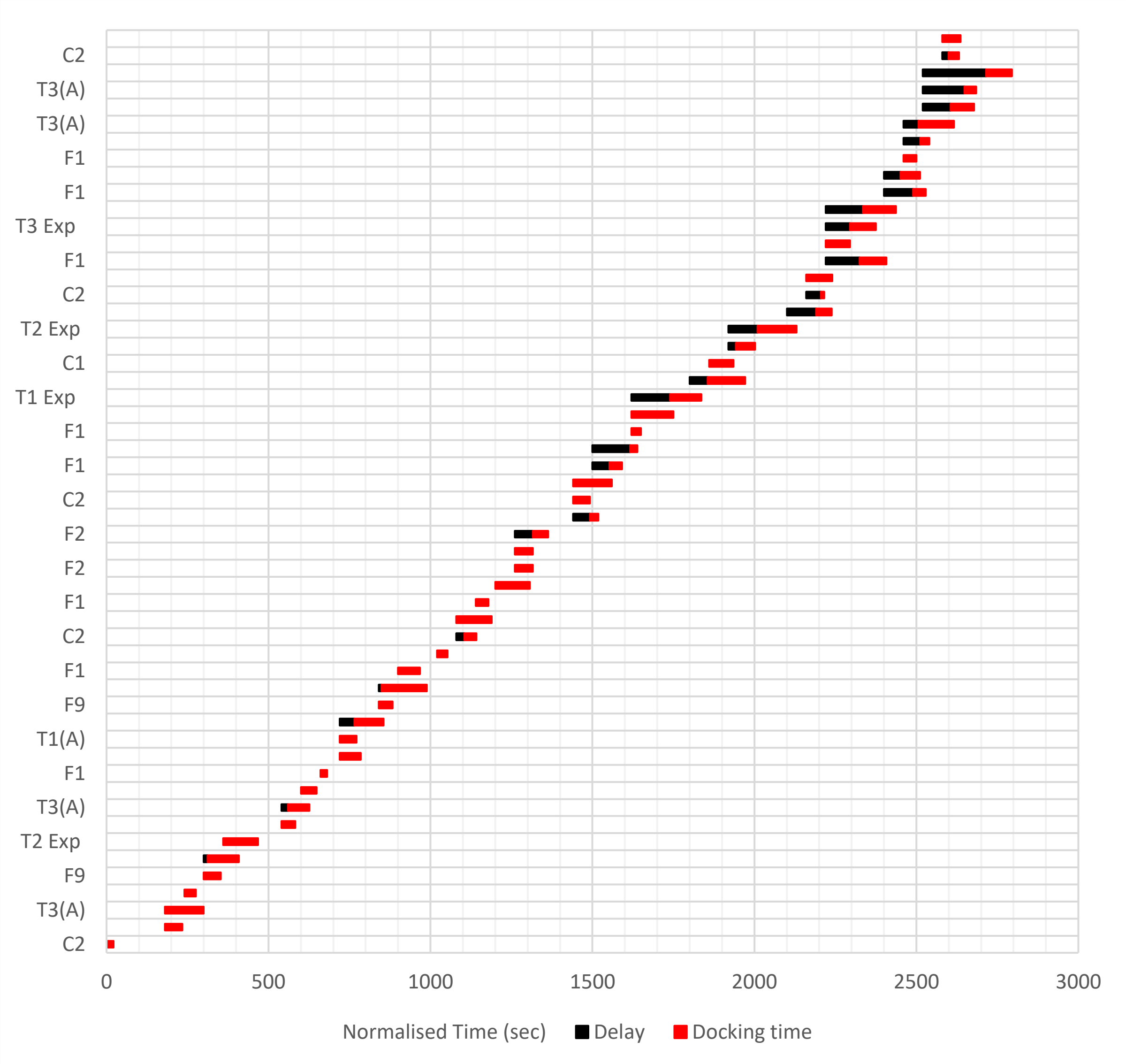


Figure 5:8 Peak hour DTs and delays at Thokoza Park Station

One bay is used for all the buses to dock at the Joburg Theatre Station, with the only exception being in the afternoon peak when the express route (T2) can dock in a separate docking bay. In the morning peak and off-peak, all routes use the same bay to dock on a first come, first-served basis. This station services seven routes, which means that the bay is always occupied. However, the DTs here were not as long as in Thokoza Park, with an average of 28 seconds for trunk buses, 23 seconds for complementary and 22 seconds for the feeders. In terms of the delays, an average of five buses is delayed during the peak hour. Figure 5.9 shows the arrival of buses at the stations and the DTs and delays during the peak hour.

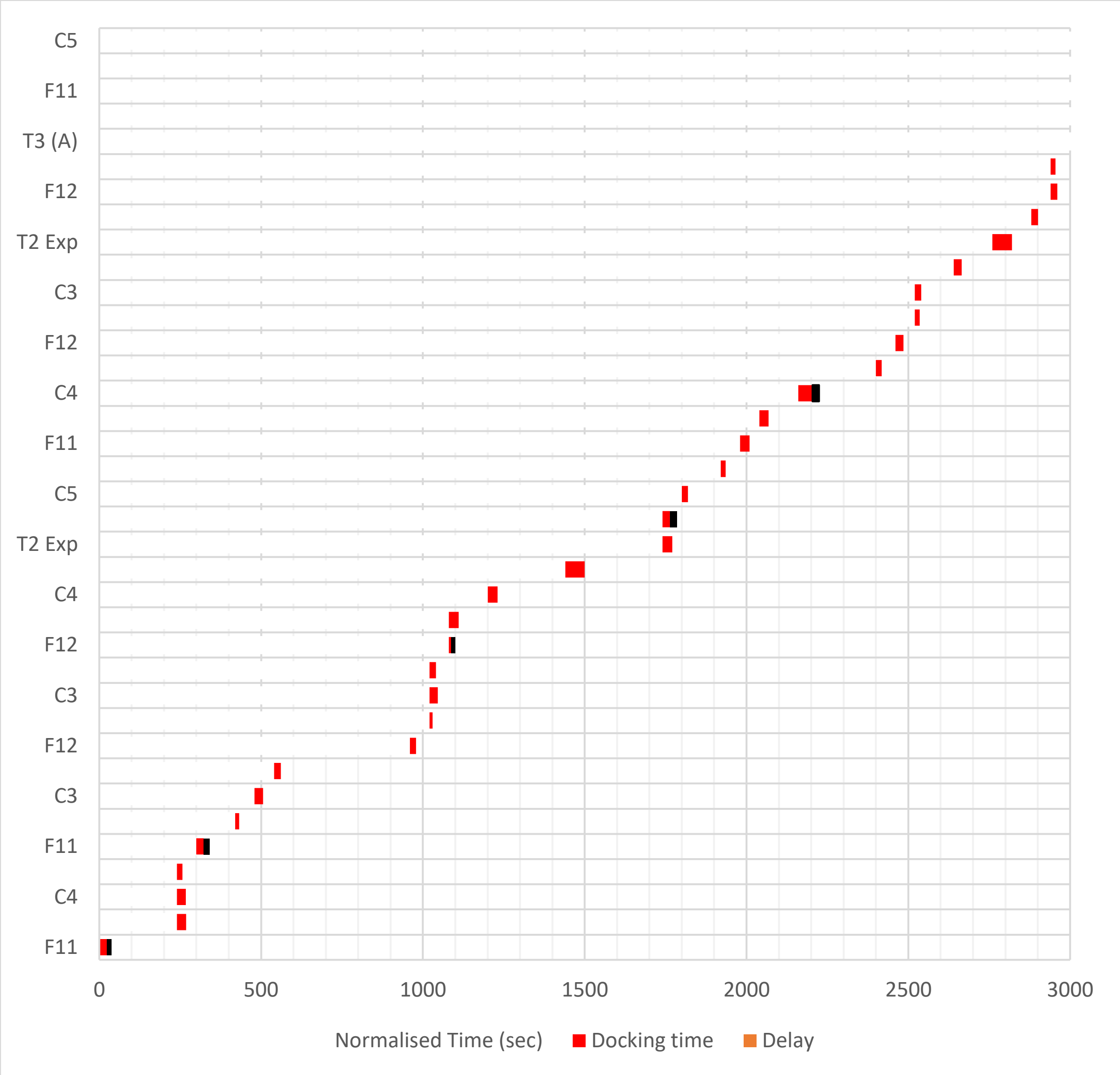


Figure 5:9 Peak hour DTs and delays at the Joburg Theatre Station

At the UJ Sophiatown Station, there is only one docking bay per direction. The average DT for trunk buses is 27 seconds and 24 seconds for complementary buses. Only two buses are delayed during the peak hour. In terms of the operations at this station, buses are basically in and out of the station, allowing each other to occupy the bay. In terms of buses arriving at the same time, this is not the norm here. Figure 5.10 shows the arrival of buses during the peak hour, their DTs and delay (if any).

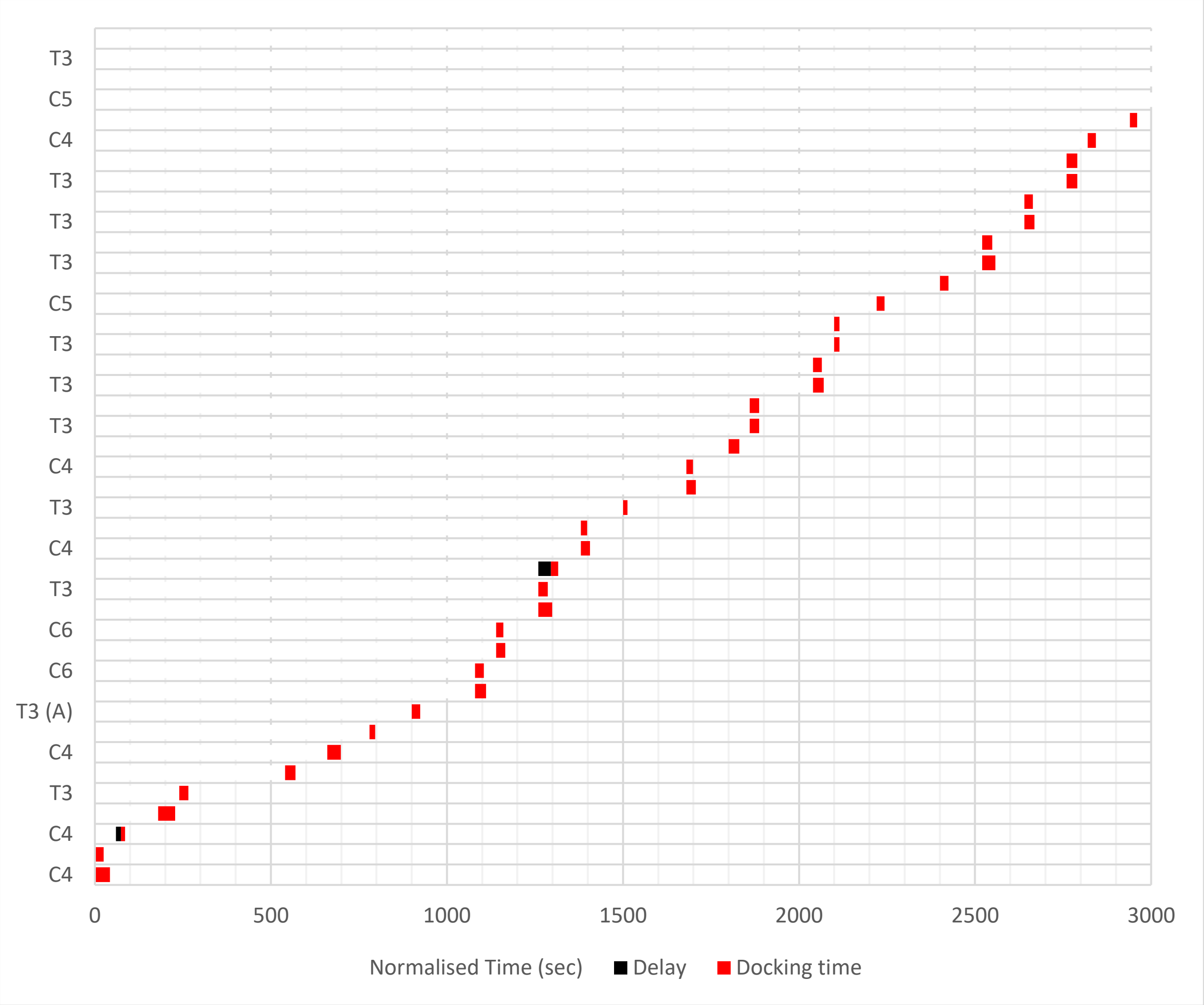


Figure 5:10 Peak hour DTs and delays at UJ Sophiatown Station

At the Orlando Stadium Station, there are two docking bays per direction. The average DT for the trunk buses is 23 seconds, and for complementary buses, it is 26 seconds. The operations at this station are quite straightforward, whereby buses come to the station, pick up and drop off passengers in the shortest time without interfering with each other. At this station, two buses are delayed during the peak hour. Figure 5.11 shows the arrival of buses in the peak hour and the time spent at the station, including any delays experienced.

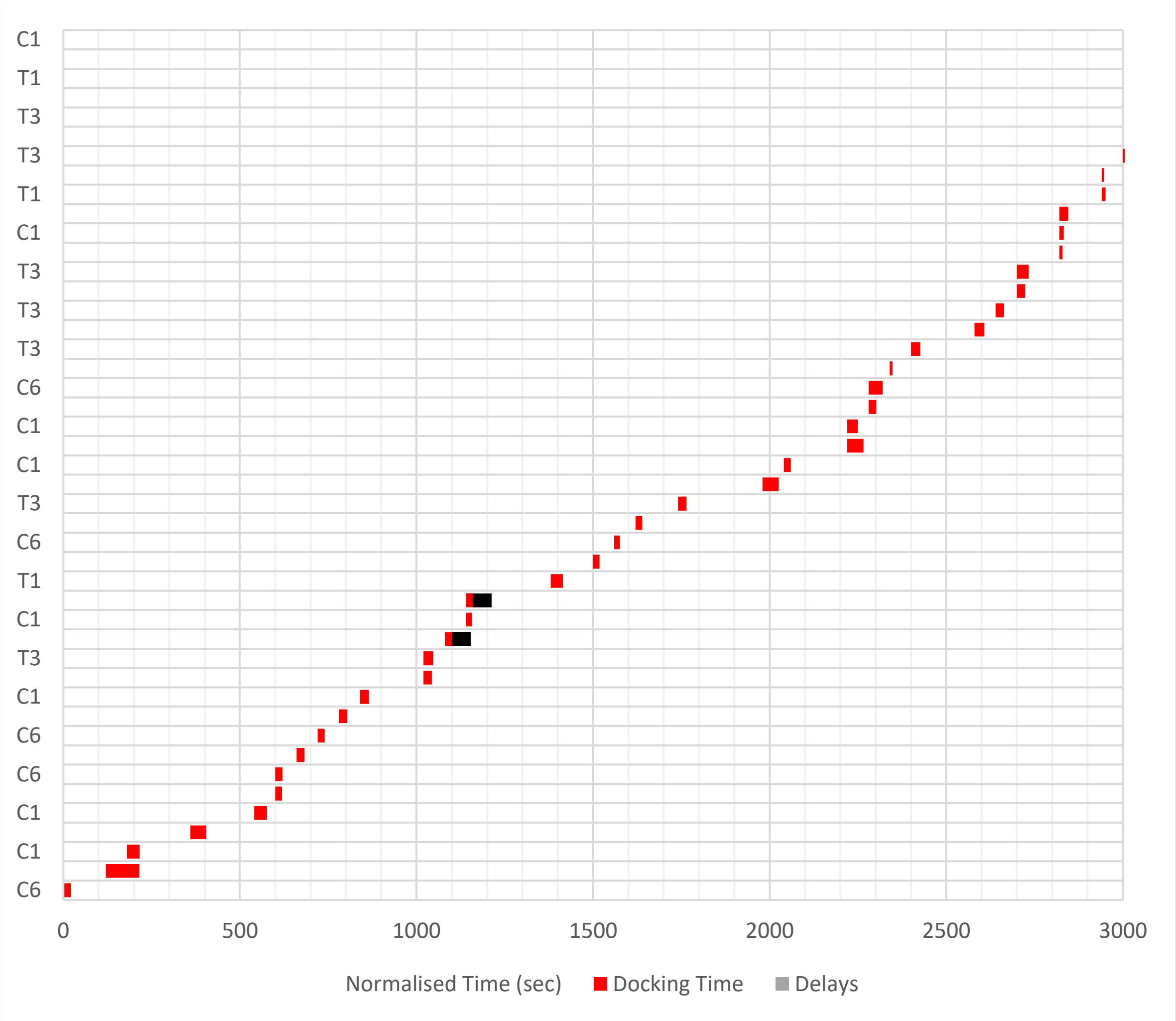


Figure 5:11 Peak hour DTs and delays at Orlando Stadium Station

At the Library Gardens Station, there are two docking bays. The picture is like that of the Thokoza Park Station, where the level of bus interference is also high. This station services nine routes, so the operations are complex. Buses were arriving simultaneously during the peaks and had to wait for each other at the station as there were only two bays available. The average DT for the trunk buses is 21 seconds, 25 seconds for the complementary buses and 36 seconds for the feeder buses. Figure 5.12 shows the arrival of buses and time spent at the station, including the delays experienced.

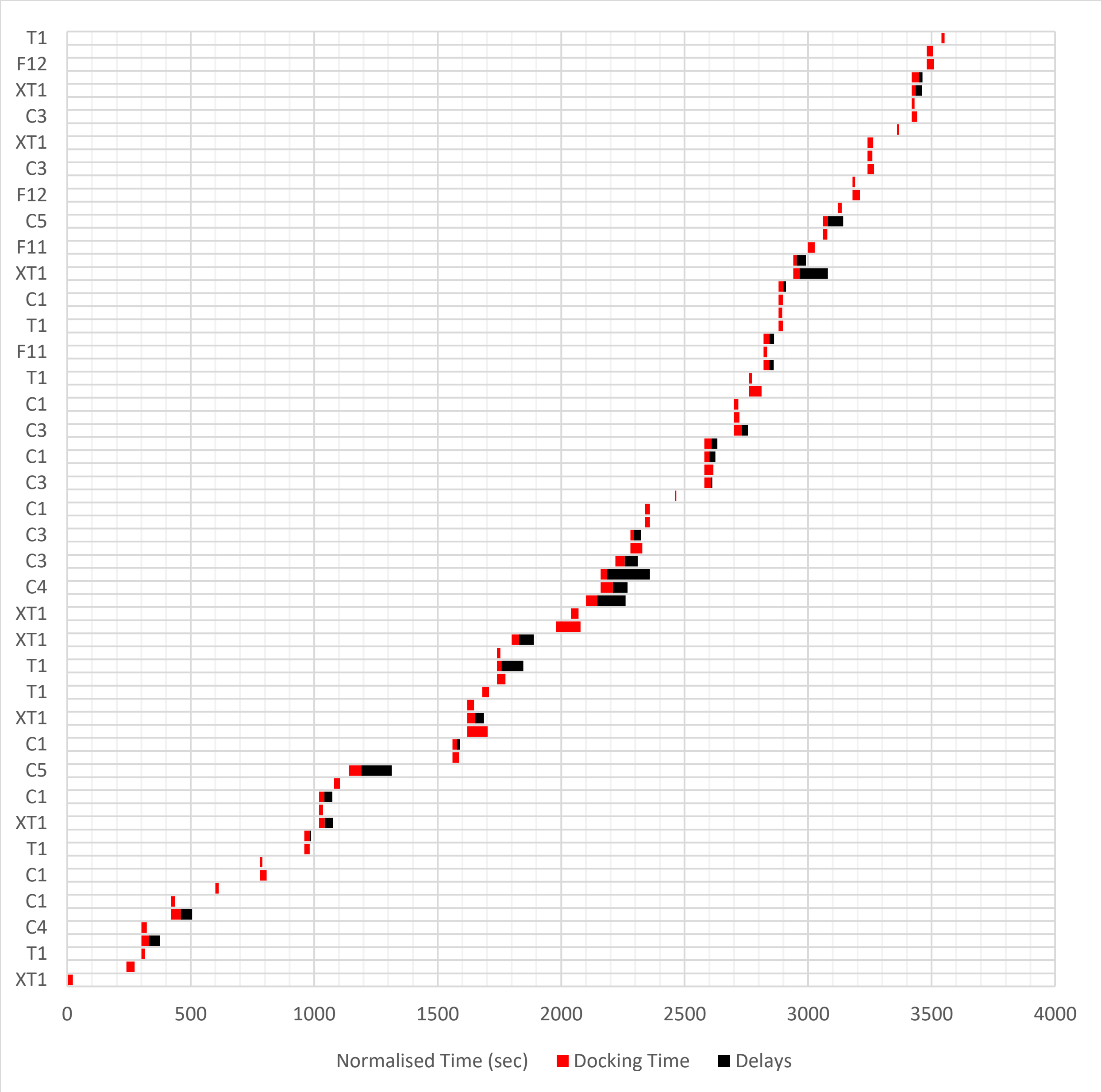


Figure 5:12 Peak hour DTs and delays at the Library Gardens Station

In summary, with regards to headway irregularity, it was expected that it would be less for the trunk-feeder network mainly due to its operations on the dedicated lane and signal prioritisation. However, those benefits could not be fully realised on the Rea Vaya system, because of the interference on the trunk corridor by minibus and private vehicles and at the station by other buses in the system. The trunk buses are subjected to other factors such as malfunctioning traffic lights (which could also be due to load reduction applicable in South Africa) and general station operations regarding the delays and lack of prioritisation of the trunk buses. All these factors affect the trunk-feeder network performance negatively.

Further analysis is conducted to determine whether complementary buses have more irregularity at their arrival at the trunk network (because hypothetically, they are more susceptible to delay on the streets). This analysis is conducted specifically for complementary routes that entered the trunk network at stations surveyed, and the same routes are surveyed again at other stations along the trunk corridor. In essence, capturing the irregularity on arrival at the trunk station and downstream, the trunk network shows two pictures: what happens outside the trunk corridor and what happens inside the trunk corridor.

The C1 complementary buses enter the trunk corridor at Orlando Stadium and use the trunk network on their way to Ellis Park Station (which is the end of the route). The buses also pass through the Library Gardens Station. The irregularity index for C1 buses at the Orlando Stadium is compared with the irregularity index at the Library Gardens (downstream on the trunk corridor); it can be seen in Figure 5.13 that there is a difference. The same is true for the C6 and C4 complementary buses (see Figure 5.14 and 5.15) that enter the trunk corridor at Orlando Stadium and UJ Sophiatown, respectively.

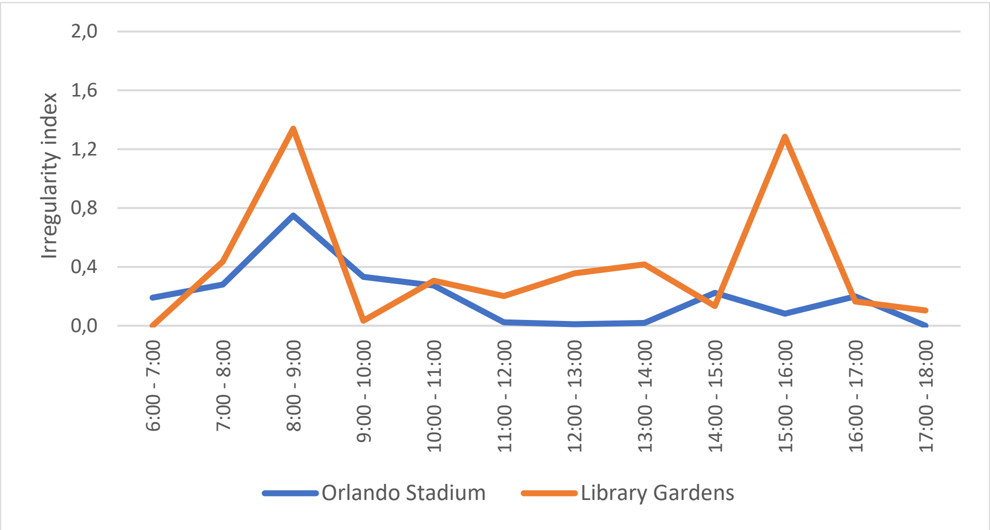


Figure 5:13 Headway irregularity index for C1 bus at different stations on the trunk network

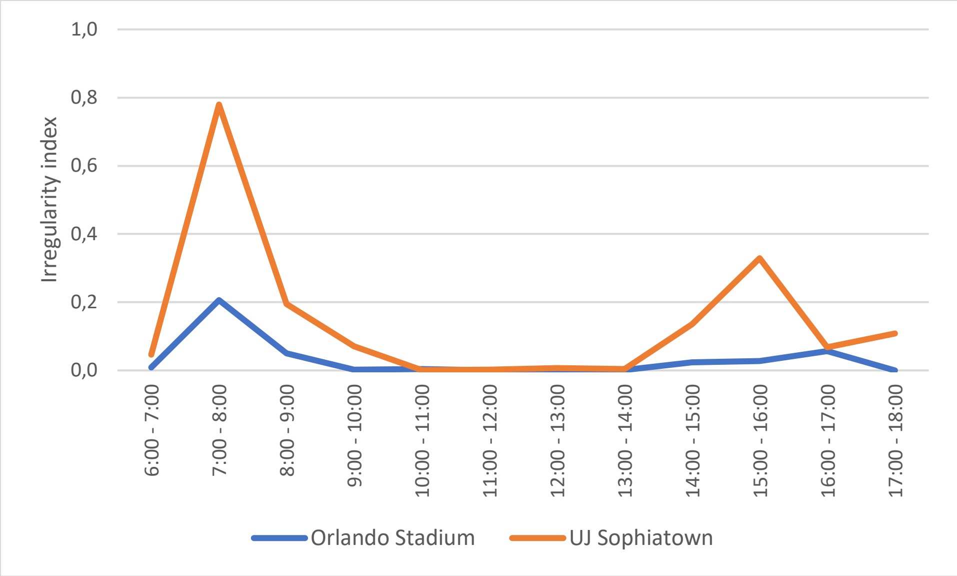


Figure 5:14 Headway irregularity index for C6 bus at different stations on the trunk network

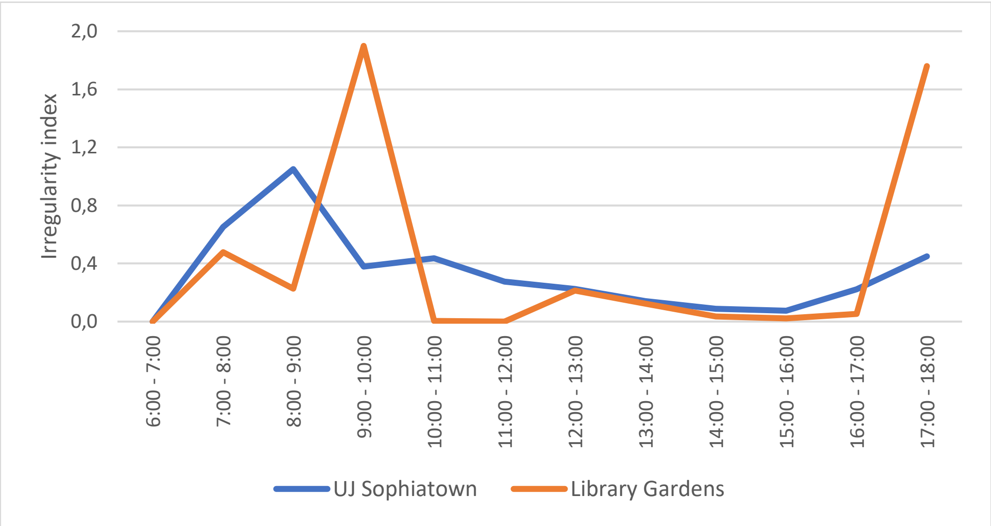


Figure 5:15 Headway irregularity index for C4 bus at different stations on the trunk network

A paired t-test is used in this case to determine whether there is a significant difference between the irregularity of the complementary buses on arrival at the station and after they traverse the trunk corridor. Since there is a time-of-day variation seen from the figures above, the data is grouped into peak (AM and PM) and off-peak data; this is also done to obtain a reasonable sample size for the test.

The null hypothesis for the paired sample test is $Irr_{before} <= Irr_{after}$, and the alternative hypothesis is that $Irr_{before} > Irr_{after}$

For both the peak and off-peak periods, the p-value is more than 0,05, so the null hypothesis is accepted (Table 5.4).

Table 5.4 Paired t-test results for complementary buses

	Peak		Off-peak	
	Before trunk	*After trunk*	*Before trunk*	*After trunk*
Mean	0,25	0,43	0,13	0,21
Variance	0,09	0,28	0,02	0,19
t Stat	-1,21		0,75	
P(T<=t) one-tail	0,11		0,22	
t Critical one-tail	1,70		1,72	

General findings

From the analysis above, it can be concluded that irregularity before the buses enter the trunk corridor is less than the irregularity after entering the trunk corridor. Hypothetically it is expected that the complementary buses would have more irregularity before joining the trunk because they are more susceptible to delays on the streets, which has nothing to do with the issues on the trunk corridor. However, the results indicate that the irregularity of the complementary buses does get worse after joining the trunk corridor. It can also be concluded that the complementary buses are also affected by station delays and interference at the stations (same as the trunk buses).

5.2. STATION SATURATION LEVELS

According to the BRT planning guide, station saturation is an important indicator used to compare direct versus trunk-feeder BRT networks. The saturation levels of all five surveyed stations are calculated using equations 12 to 18, and the results are shown in Table 5.5. The saturation level is calculated for the peak hour only. From the results, Thokoza Park has the highest saturation level (a total of 85%), and the Joburg Theatre Station has the lowest saturation level (at 15,1%), which is consistent with the observations during the station surveys. The DTs and delays for buses at Thokoza Park were higher than those at the Joburg Theatre Station, contributing to the high saturation levels. The Library Gardens Station has the second-highest saturation levels, which was also consistent with what was observed during the station surveys. Also, from the following results, a relationship can be deduced between the number of routes and the saturation level, so the more routes serviced at a station, the higher the saturation level.

Table 5.5 Saturation levels for all the surveyed stations

Station	Saturation (T) (%)	Saturation (F) (%)	Saturation (C) (%)	Total Saturation (%)
Thokoza Park	45	19	21	85
Joburg Theatre	5	5,5	4	15
UJ Sophiatown	13	N/A	7	20
Orlando Stadium	10	N/A	9	20
Library Gardens	21	7	22	51

Counterfactual analysis is used to gain a deeper understanding of the direct versus trunk-feeder BRT question and how that relates to station saturation. This was done to determine the effects on station saturation if the system is completely trunk-feeder or completely direct, while controlling for station design, headway variability and demand. The analysis is extended to more stations along the trunk corridor. The design criteria are as follows:

For the trunk-feeder network

- 18m articulated buses are used for the trunk corridor, and 12m standard buses are used off-trunk as feeders;
- convert all complementary routes to trunk and feeder routes. A determination was done of the number of trips required if the complementary routes were operated using trunk and feeders (keeping the demand as the constant);
- the average DTs for the trunk and feeder buses are calculated using data from the station survey data; and
- an average kerb length of 50m is used. A constant station size is used for comparison purposes. It is acknowledged that actual station designs are based on current direct and trunk-feeder configurations, which would influence the hypothetical comparisons if used.

For the direct network

- 18m articulated buses used for the trunk corridor and 12m standard buses are used on and off-trunk as complementary routes;
- convert all feeder routes to complementary routes: the number of trunk buses is reduced because complementary buses were added. The demand on the trunk corridor is now serviced by trunk and complementary buses;
- the average DTs for the trunk and complementary buses are calculated from the station survey data; and

- an average kerb length of 50m is used.

The results for the station saturation levels for the counterfactual analysis are indicated in Table 5.6.

Table 5.6 Saturation levels for direct and trunk-feeder networks for different stations along the trunk network

		Trunk-feeder			Direct		
Station	No. of routes	Saturation (T)	Saturation (F)	Total saturation	Saturation (T)	Saturation (C)	Total saturation
Old Synagogue	1	19%	0%	19%	19%	0%	19%
Fashion Square North	2	21%	1%	22%	19%	1%	20%
Industria West	2	23%	4%	27%	18%	3%	22%
Diepkloof	3	34%	7%	41%	25%	6%	31%
Carlton Centre East	3	29%	8%	37%	19%	7%	26%
Helen Joseph Hospital	3	25%	6%	31%	18%	5%	23%
Rissik Station	3	26%	1%	27%	24%	1%	25%
Milpark	4	29%	9%	38%	18%	7%	26%
Park Station	4	26%	4%	29%	24%	3%	28%
UJ Sophiatown	4	29%	9%	38%	18%	5%	24%
Orlando Stadium	4	51%	11%	62%	38%	9%	47%
Chancellor House East	5	35%	11%	46%	25%	9%	35%
Lakeview	7	48%	11%	60%	44%	10%	53%
Thokoza Park	7	48%	18%	67%	44%	16%	59%
Joburg Theatre	7	32%	11%	43%	24%	9%	34%
Library Gardens	9	59%	18%	77%	44%	15%	59%

The saturation for the trunk-feeder network is higher than that of the direct network from the results above. The mean percentage increase is calculated to be 25% higher for the trunk-feeder network compared to the direcr network. The saturation level ranges from 19% to 77% for the trunk-feeder network and 19% to 59% for the direct network. Due to the high DTs on the trunk-feeder network, this is expected. From the results, it can also be concluded that a relationship exists between the number of routes and the saturation level: the more routes serviced at a station, the higher the saturation level. By performing a correlation analysis between the number of routes and the station saturation level of the trunk-feeder and direct network, this is also confirmed. The correlation coefficient is 0,86 and 0,85 for the trunk-feeder and direct network respectively, indicating a strong linear relationship between the number of routes and saturation level.

5.3. OPERATING SPEED

The average vehicle operating speeds per route are calculated using Equation 19 for the AM, PM, and off-peak periods (Table 5.7). The data are from the on-board survey.

Table 5.7 Vehicle operating speeds for all routes in the AM, PM and off-peak

Vehicle operating speed (Km/h)			
	AM peak	Off-peak	PM peak
T1	31	32	28
T2	28	N/A	26
T3	26	28	32
C1	26	31	25
C2	24	27	30
C3	14	14	12
C4	20	21	17
C5	18	21	21
C6	20	29	23
F1	28	29	30
F2	28	26	31
F3	24	23	22
F4	27	31	24
F5	26	30	29
F6	25	28	36
F7	34	38	32
F8	22	24	23
F9	26	25	23
F10	27	27	24
F11	16	17	15
F12	24	29	21

The average speed for trunk buses is 30 km/h. The average speed for complementary buses is 20 km/h. The average speeds for feeder buses are 25 km/h and higher than the complementary routes, which is unusual as they operate exclusively in mixed traffic with kerbside boarding.

Taking a closer look at the roads that the feeder and complementary buses operate on, the following can be said:

- the C3 complementary route operates in the Johannesburg CBD in a high congestion zone, which explains the average speed of 12 km/h (the route diagram is attached in Appendix C);
- the C4 and C5 complementary routes operate on Beyers Naude and Ontdekkers (Appendix C), major arterial routes with high congestion levels before they enter the trunk corridor, which explains the low speeds of 20 km/h; and
- the feeder routes operate mostly on lower-class roads with less congestion in areas such as Soweto. That explains why they can maintain reasonable average speeds.

Ticketing data is used to obtain the overall passenger trip time from tag-in at the first stop/station to tag-out at the final stop/station. The passenger trip speed is calculated from the distance and passenger trip time using Equation 20. For the comparative analysis, trips using both feeder and trunk are compared with complementary trips, with both scenarios representing off trunk and trunk movements.

A histogram function on Excel is used to determine the distribution of the passenger trip speed using ranges of 5 km/h to 50 km/h (Figure 5.16).

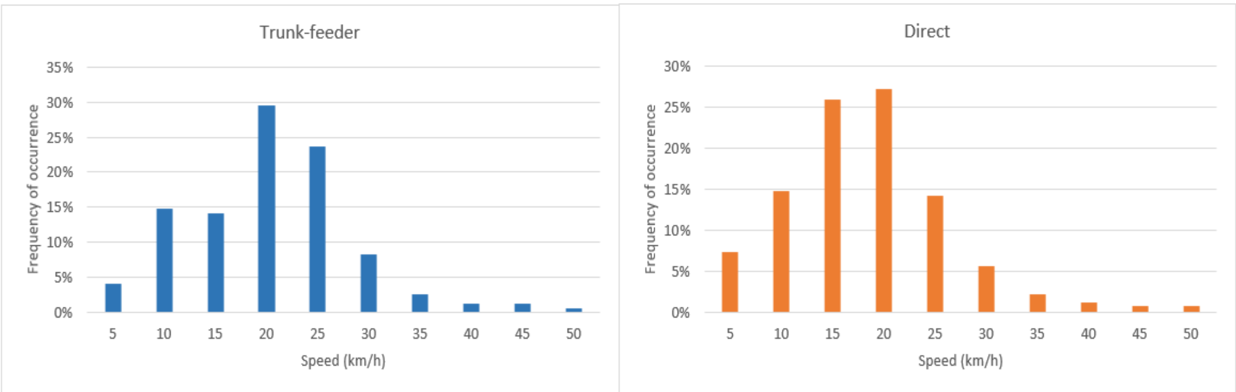


Figure 5:16 Trip speed for trunk-feeder and direct networks

For the feeder and trunk trips, 67% of the passenger trip speeds are within the range of 20 km/h and above, whereas for complementary trips, 52% of the passenger trip speeds are within the range of 20 km/h and above. Seven per cent of the complementary trips has passenger trip speeds in the range of 5 km/h range, and only 4% of the feeder and trunk trips have passenger trip speed in the range of 5 km/h. The average speeds for the trunk-feeder network range from 20 to 25 km/h and it is 15 to 20 km/h for the direct network. The feeder and trunk trips include a transfer, and complementary trips are without a transfer. A transfer results in additional trip time; hence it was expected that the complementary trips would have overall lower travel time and higher speeds. However, according to the results, the feeder and trunk trips have higher passenger trip speeds compared to the complementary routes, even with the trip being disrupted for passengers to transfer. Now looking at the vehicle operating speeds, the complementary routes have low operating speeds that have been attributed to the highly congested arterial routes that they operate on before joining the trunk corridor. Hence the passenger trip speeds for the complementary trips are lower. Also, the frequency of the trunk-feeder network (see Section 4.5.1) is high so that passengers transferring do not have to wait long to connect. In conclusion, the high vehicle operating speeds and frequency of the trunk and feeder routes offset the effects caused by the transfer.

5.4. LOAD FACTOR

The load factor is calculated using Equation 21, and this is done per route type for the AM peak, off-peak, and PM peak period, as seen in Table 5.8. The data are from the on-board survey.

Table 5.8 Load factor for all route types

Route name	AM peak %	Off-peak %	PM peak %	Peak average %
T1	77	85	73	75
T2	97	N/A	67	82
T3	79	74	100	90
C1	64	27	44	54
C2	79	26	45	62
C3	27	27	27	27
C4	96	35	80	88
C5	70	13	64	67
C6	97	27	76	87
F1	96	27	80	88
F2	96	76	71	84
F3	71	27	62	67
F4	68	35	60	64
F5	82	27	67	75
F6	71	27	100	86
F7	30	27	64	47
F8	52	27	30	41
F9	81	27	96	89
F10	64	13	58	61
F11	48	26	59	54
F12	54	26	27	41

The trunk routes were well used in the peak and off-peak periods, with average peak hour utilisation of 80%. The complementary routes are moderately used in the peak periods with average peak hour utilisation of 60% to 70%. However, the average off-peak utilisation is at 25%. The feeder routes are also moderately used in the peak periods, with average peak hour utilisation at 65% to 70%. The average off-peak utilisation is at 30%.

A closer look at the supply side indicates that the trunk routes use articulated 18m buses with a high frequency during the peak time and a reduced frequency off-peak, as explained in Section 4.6. The feeder and complementary routes use standard 12m buses with higher frequency in the peak period compared to the off-peak period. Based on the results, the trunk routes are succeeding in matching the demand to the capacity provided. The high utilisation values confirm this. The feeder routes also achieve results in matching demand to the capacity provided; however, this is true only for the peak periods. During the off-peak period, the supply (capacity) is more than the demand, resulting in low utilisation values even though the frequencies have been reduced. The same can be said about the complementary routes. The low off-peak ridership is attributed to the high peak-to-base ratio mentioned in the previous section, where most travel happens in the peak periods.

According to the analytical models, the trunk-feeder network diminishes idle capacity by using large trunk buses in the dense environment of the corridor and smaller feeder buses outside it. The problem with direct (complementary) routes is idle capacity, as the same bus size is used for the entire route, regardless of the demand distribution. A statistical test is used to prove or disprove the hypothesis that trunk and feeder routes have a higher load factor than complementary routes.

A two-sample independent t-test (one-tail) is used for the hypothesis testing for the AM peak, off-peak, and PM peak. The results are shown in Table 5.9.

The null hypothesis: $Load_{T\text{-}F} <= Load_C$
The alternative hypothesis: $Load_{T\text{-}F} > Load_C$

Table 5.9 Independent t-test for load factor

t-Test: Two-Sample Assuming Unequal Variances						
	AM peak		*Off-peak*		*PM peak*	
	T-F	*C*	*T-F*	*C*	*T-F*	*C*
Mean	71,06	72,16	37,42	25,83	67,6	56
t Stat	-0,09		1,72		1,14	
P(T<=t) one-tail	0,46		0,05		0,01	
t Critical one-tail	1,89		1,73		1,81	

For the AM peak, the p-value is more than the significance level of 0.05, so the null is accepted. From the results the mean load factor for the trunk and feeder routes is less than that of the complementary routes but the difference is not significant. For the off-peak, the alternative hypothesis is accepted, and trunk and feeder routes have a higher load factor than complementary routes. For the PM peak, the alternative hypothesis is accepted and the load factor for the trunk and feeder routes is higher than that of the complementary routes.

5.5. OPERATING COSTS

Since some of the costs are not available from the bus operator, an operating cost model was developed to estimate and compare the operating costs per kilometre and cost per passenger for the trunk, feeder, and complementary routes of the Rea Vaya BRT system. The model considers the bus and driver cost and excludes facilities and station costs as well as general staff costs shared by all the route types. Regarding the driver costs, there are three shifts per day to cater for the current operating hours.

The route information (route length, trips per day) and the bus information (capital costs, maintenance cost per kilometre, tyre cost per kilometre, insurance costs, licencing costs, and fuel consumption) are sourced from the operator for the year 2019. Detailed information is included in Appendix F.

The following equations are used to calculate the monthly costs:

Fuel cost $= \frac{Number\ of\ km\ per\ month}{100} * Fuel\ consumption\ per\ 100km * Fuel\ cost\ per\ litre$ (23)

Maintenance cost $= Maintenance\ cost\ per\ km * number\ of\ km\ per\ month$ (24)

Tyre cost $= Tyre\ cost\ per\ km * number\ of\ km\ per\ month$ (25)

Labour $= (Driver\ rate\ per\ month * no.\ of\ drivers\ weekday)$ (26)

Uniform $= Uniform\ rate * number\ of\ drivers$ (27)

Training $= Training\ rate * number\ of\ drivers$ (28)

For trunk, complementary and feeder routes, the associated costs are noted in Table 5.10.

The total operating costs are made up of vehicle costs and driver costs. For trunk routes, the cost drivers are fuel, maintenance and labour, and vehicle repayments. The reason for this is that the trip lengths are longer (around 25 km) and operated at high frequencies, resulting in high vehicle kilometres travelled per month and a larger fleet size required (around 100 trunk buses). Also, the articulated buses cost R5,2 million each, resulting in higher vehicle repayments. On the complementary routes, the standard buses cost R4,3 million, resulting in lower vehicle repayment costs compared to the trunk routes. As with the trunk routes, the complementary routes also have a long trip length (average of 17 km) and a large fleet size for the peak period (around 70 buses used). In the case of feeder buses, the fuel, maintenance, labour, and vehicle repayments are not as high because the trip length for the feeder buses is short (calculated as 20% of the total trip length for Rea Vaya). Also, the number of buses required to run the services is not high (an average of four buses per route).

Table 5.10 Operating costs per kilometre and cost per passenger for trunk, complementary and feeder routes

Costs	Trunk	Complementary	Feeder
Vehicle purchase price	5 200 000	4 300 000	4 300 000
Vehicle repayment	95 708	79 159	79 159
Vehicle operating costs			
Fuel	1 110 227,12	507 164,54	177 164,94
Maintenance	1 590 999,96	665 601,07	224 636,30
Tyres	64 030,69	29 060,67	9 8070,80
Insurance	61 750	122 037	5 106
Overheads	282 700,78	90 077,78	41 071,53
Driver costs			
Labour	871 150	215 495,00	87 115
Leave allowance	87 115	31 363,50	8 711,50
Uniform	13 463	4 889,34	1 346,34
UIF allowance	8 711,50	3 163,65	871,15
Training	15 146,80	5508,58	1514,68
Total costs			
Vehicle operating costs	3 109 709	1 342 407	451 787
Driver costs	995 587	361 555	99 559
Total operating costs	4 105 295	1 703 962	551 345
Total vehicle repayment	3 030 753,33	910 328,50	250 670,17
Cost per km	**39,89**	**30,34**	**29,51**
Cost per passenger	**11,68**	**17,08**	**6,19**

The difference in average costs per kilometre between the complementary and feeder route types is not significant, and the average cost per kilometre for the trunk routes is the highest. The cost per passenger is lower for the feeder and trunk routes and highest for the complementary routes. Looking at economies of density, there is a saving in operating costs that can be achieved by using large vehicles in the main streets or avenues that receive passengers from many possible feeder lines using smaller vehicles. It is cheaper per passenger as costs are spread over a larger passenger number. The capacity is increased without necessarily increasing the number of vehicles or even the kilometres travelled. Due to the benefit of economies of density, the trunk route has a lower cost per passenger compared to the complementary routes. The trunk routes benefit from the cost advantages of increasing the flow on a trunk link by using larger vehicles.

Idle capacity has an impact on the operating costs (Gshwender et al., 2016). According to the analytical models, direct routes present idle capacity because the same capacity is supplied for the entire route (using the same bus size). Counterfactual analysis is deployed in this instance to determine the impact of changing all the complementary routes into trunk and feeder routes. For this analysis, the route is divided into two sections: the section outside the trunk that is converted into a feeder route and the section inside the trunk corridors that is converted into a trunk route. The converted trunk routes start when the complementary route enters the trunk corridor and not necessarily at the start of the trunk corridor itself, so there will be no upstream unused capacity resulting from this conversion. Would the costs increase or decrease based on the capacity changes (on the supply side)? From the results (Table 5.11), the unit costs per kilometre would increase if the complementary routes were replaced with trunk and feeder buses, but the cost per passenger would decrease, which is consistent with the results obtained previously. It can be concluded that the trunk-feeder network has a lower cost per passenger compared to the direct network. However, concerning the unit cost (cost per kilometre), it is higher for the trunk-feeder network (particularly the trunk) due to the long trip lengths and increased fleet size.

Table 5.11 Counterfactual analysis results for converting complementary routes to trunk and feeder routes

Counterfactual analysis			
	Complementary	Trunk	Feeder
Cost per kilometre	R30,34	R34,03	R32,34
Cost per passenger	R17,08	R12,97	R4,26

5.5.1. Limitations

As stated earlier, the infrastructure costs (facilities, station costs and general staff costs) are excluded. A trunk-feeder network requires a transfer station to accommodate passengers transferring from the feeders to the trunk buses (and vice versa). This mandatory requirement was not quantified in this study because of the station size to accommodate transferring passengers. This extra station space required would have an impact on the capital cost.

6. CONCLUSIONS AND RECOMMENDATIONS

This research aimed to explore the strengths and weaknesses of two BRT-based network types: trunk-feeder (buses operating inside and outside the BRT trunk corridor are segregated and operate independently) and direct (buses operating outside the trunk corridor can enter and leave it, providing additional services in the corridor). The approach taken was empirical and evidence-based, from a passenger, operator, and owner perspective, using the City of Johannesburg BRT system (Rea Vaya) as a case study.

The literature on bus system design suggests several advantages of direct over trunk and feeder routes, especially for medium-sized systems with lower passenger demand. However, theoretical and simulation studies usually make multiple assumptions and simplifications, ignoring real-world issues. It can be concluded that benchmarking reports for BRT systems worldwide have not delivered a comprehensive empirical performance analysis of BRT systems. This study aims to fill this gap by measuring and analysing their actual performance in the context of an operating BRT system with both networks.

Theoretical models used to compare direct versus trunk-feeder BRT networks have yielded different results and have provided comparative insights into the different BRT networks. Trunk-feeder is considered superior for short trips because when there is a low proportion of long trips (meaning no local trips), then there would be fewer transferring passengers from the feeders to the trunk network. Also, trunk-feeder is not ideal for long trip lengths because the operator's cost increased due to longer cycle times (including transferring time) and increased fleet size. The case for the trunk-feeder network rests on economies of density, which translates as savings in operating costs. This saving results from using larger vehicles in the main streets or avenues to achieve more capacity (without necessarily increasing the number of vehicles) and a cheaper cost per passenger (costs are spread over a larger passenger number). Therefore, this structure is attractive because of the flexibility it provides in terms of vehicle sizes. With direct routes, the main advantage is that transfers are avoided. Transfers do not only disrupt a trip but also make the overall system slower (due to additional walking and waiting time). Direct networks are superior when there is a high proportion of long trips (long trip length), and this is because idle capacity is low.

In this study, a set of indicators was developed to compare direct versus trunk-feeder BRT networks and comment on some of these theoretical findings. These indicators include headway irregularity, station saturation levels, operating speed, load factor and operating costs.

Counterfactual analysis was also used to explore the findings further and control for external factors that affected the results but had nothing to do with the system being direct or trunk-feeder.

The results can be summarised as follows:

- **Headway irregularity**

It was expected that the direct network would have a higher headway irregularity compared to the trunk-feeder network. This is because the direct network was subjected to mixed traffic operations and external factors such as congestion, road incidents and accidents, which would affect schedule adherence and headway regularity. For Rea Vaya, this was not the case, and there was no significant difference between the irregularity of the direct versus trunk-feeder networks because the dedicated lane was subjected to interference by minibus and private vehicles. The trunk corridor was subjected to other factors, such as malfunctioning traffic lights (also because of load shedding) and general station operations concerning delays and lack of prioritisation of the trunk buses. An analysis was also carried out to determine whether the complementary buses are more irregular on their arrival on the trunk network. The results indicate that the irregularity got worse after entering the trunk corridor.

- **Station saturation level**

It was expected that the trunk-feeder BRT network would have a higher saturation level because the DTs are presumably longer. After all, passengers must transfer from a feeder bus onto a trunk bus (and vice versa). A formula was developed to calculate the saturation level outside the station. Furthermore, an analysis was conducted to determine the effects on station saturation if the system was completely direct or trunk-feeder, at the same time controlling for station design, headway variability and demand. This calculation was extended to other stations along the trunk corridor beyond the five stations that were surveyed. In the Rea Vaya BRT system, the saturation for the trunk-feeder is indeed higher than that of the direct network. According to the results, it can also be concluded that a relationship exists between the number of routes and the saturation level, so the more routes serviced at a station, the higher the saturation level.

- **Vehicle operating speed and passenger trip speed**

Ticketing data was used to determine the passenger trip travel time: the difference between the boarding and the alighting time. The passenger trip speed was computed using the passenger trip travel time and the distance between boarding and alighting. For the analysis, feeder and trunk trips (representing the trunk-feeder network) are compared with complementary trips (representing the direct network), resulting in a comparison of trunk to off-trunk movements. Hypothetically, the trunk-feeder network would have a longer travel time and slower speeds because of the mandatory transfer. According to the results, the feeder and trunk trips have faster passenger trip speed compared to the complementary routes, even with the trip being disrupted for passengers to transfer. This can be attributed to the vehicle operating speeds for the different route types. In terms of the vehicle operating speeds, the average speeds for trunk buses are very good at 30 km/h. The average speeds for complementary buses are acceptable at 20 km/h. The average speeds for feeder buses are excellent at 25 km/h, higher than the complementary routes, which is unusual, as they operate exclusively in mixed traffic with kerbside boarding. The reason for this is that the feeder buses operate on low-density local roads with less traffic, where the complementary routes operate on major arterials with high levels of congestion. Concerning the trunk routes, one would expect the speeds to be higher than 30 km/h because they operate solely on the dedicated lanes, but other factors (interference, lack of prioritisation, traffic signal) prevent the trunk buses from achieving high speeds. It can be concluded that the potential time savings of complementary routes through avoiding transfers does not materialise as it is more than offset by the slow vehicle speeds on mixed traffic routes.

- **Load factor**

According to the analytical models, one of the benefits of trunk-feeder networks is that it diminishes idle capacity. By using small vehicle sizes for low-density areas and using larger vehicle sizes for the main streets, matching supply and demand closely, this can be achieved. For the Rea Vaya system, the trunk routes were well used in the peak and off-peak periods, with average peak hour utilisation above 80%. The complementary routes are moderately used in the peak periods with an average peak hour utilisation of 70%. However, the off-peak utilisation was at 25%. The feeder routes were also moderately used in the peak periods, with average peak hour utilisation at 65% to 70%. The off-peak utilisation was at 30%. A statistical t-test was performed comparing the load factor for trunk and feeder buses with complementary buses. The load factor is the similar for both routes during the AM peak, but trunk and feeder routes have a higher load factor during the off-peak and PM peak.

- **Operating costs**

An operating cost model was developed to compare the operating costs per kilometre and the cost per passenger for trunk, feeder, and complementary routes of the Rea Vaya BRT system. The model considered the bus and driver cost and excluded facilities, station costs and general staff costs shared by all route types. It was hypothesised that the trunk-feeder networks might have lower operating costs due to the possibility of using smaller vehicles on the feeder routes and larger vehicles on trunks, thus matching supply more closely with demand on different sections of the route. The operating costs per kilometre were highest for the trunk routes and lowest for the feeder routes. The costs for the trunk routes are high because of increased cycle times (and long routes) and increased fleet size requirement (more buses). The feeder routes are shorter and quicker to operate (traverse on low-density roads with less congestion). It is more expensive per passenger to operate a complementary route. It is cheaper per passenger to operate larger vehicles on main avenues with high demand. This saving is because of using larger vehicles in the main streets or avenues to achieve more capacity (without necessarily increasing the number of vehicles) and a cheaper cost per passenger (costs are spread over a larger passenger number) (Table 6.1).

Table 6.1 Average costs per kilometre and costs per passengers for trunk, feeder, and complementary buses

	Trunk **R**	**Complementary** **R**	**Feeder** **R**
Operating costs per kilometre	39,89	30,34	29,51
Cost per passenger	11,68	17,08	6,19

Counterfactual analysis was deployed in this instance to determine the impact of changing all the complementary routes into trunk and feeder routes. For this analysis, the route is divided into two sections: the section outside the trunk that is converted into feeder route and the section inside the trunk corridor converted into a trunk route. From the results, the unit costs per kilometre increase if the complementary routes are replaced with trunk and feeder buses, but the cost per passenger decreases. From a cost perspective, trunk routes work best for densely populated areas but not over long distances.

Regarding this specific case study (on the Rea Vaya BRT system) and the analysis conducted, several valuable insights were gained. For instance, the operations management at the stations (lack of prioritisation of the trunk buses and sharing of docking bays) and interference (by other vehicles) influence the trunk corridor, specifically in terms of the headway regularity and operating speeds. Although punctuality and availability were not measured specifically as indicators for this study, the random arrivals of the buses captured as part of the station surveys indicated little to no schedule adherence, which is perhaps worth further investigation. The high demand peak-to-base ratio observed in Johannesburg is consistent with the low off-peak utilisation, especially on the feeder and complementary buses. It is also consistent with the spatial planning in South Africa, where low-income people live far away from employment opportunities (Scorcia & Munoz-Raskin, 2017).

Regarding the trunk routes, the utilisation off-peak was still good, which could be attributed to the different land uses that the trunk corridor serves (hospitals, university, sports stadium, theatres, CBD) so that travel is not only during the peak periods. In Rea Vaya's case, the long trunk routes affected the costs per kilometre due to high vehicle kilometres travelled and longer cycle time. Also, the trunk buses were almost R1 million more expensive than standard buses, and they can only be operated on the trunk infrastructure.

Overall, the results indicate a mixed view with regards to direct versus trunk-feeder BRT networks in a South African context. Based on the indicators used in this study, the evidence shows that there are instances where the direct network was superior to the trunk-feeder network, beyond what was established in the literature studies. The direct network performed better in terms of headway reliability, thus disproving the initial hypothesis that the trunk-feeder network would perform better in this regard. The dwell times were lower for the direct network, and this has a potential to decrease travel time, provided that other external factors (such as congestion) are not an issue. The direct network also demonstrated a high load factor during peak which was consistent with the high peak to base ratio observed in South Africa. Also from a cost perspective, it is cheaper per kilometre to operate complementary buses (direct network).

It is crucial to create a public transport system that addresses the needs of the people, that is relevant to the environment in which it is deployed and is agile (demand responsive). Based on the technological advancements (4^{th} industrial revolution) and the recent pandemic (Covid-19), it has become increasingly important to restructure the thinking, especially in terms of transport infrastructure.

The following recommendations are based on this study:

- Better attention needs to be paid to the station operations to minimise the delays at the station.
- Law enforcement needs to be deployed around the trunk corridor to manage interference by other motorists.
- When planning off trunk routes, the operating environment need to be considered, and highly trafficked arterial roads must be avoided.

- The high peak to base ratio needs to be considered especially when planning for off-peak services with low load factor.
- Instead of long trunk routes, high occupancy vehicle lanes should be considered. This could also reduce travel time and the impacts of congestion on normal mixed traffic roads.
- Regarding the feeders to the trunk network, other modes (not only buses) should be considered as feeders to the system. The integration of other modes into the Rea Vaya system should be considered (for example, formal park-and-rides, minibus taxis, non-motorised transport). This was specifically seen at the Thokoza Park Station, where there is an informal park-and-ride facility and passengers used their private vehicles to access the trunk corridor.
- Perhaps a combination of direct and trunk-feeder networks needs to be considered more so that the advantages offered by both networks can be realised.

Future research requires:

- Station size requirements, given technological advancement. For instance, the introduction of Europay Mastercard and Visa cards and online services to load cards or even log customer complaints or queries will reduce the need to provide vending machines and customer service centres.
- The vehicle requirements in terms of infrastructure (number of lanes, width, docking bays, and so forth) were not considered part of this study, and further investigation is needed.
- Costs are significant, not only operating costs but capital costs as well. A detailed costing analysis is required to determine the total cost of ownership to assess the long-term value of the system.

REFERENCES

Ackerman, J.S. 2015. *Optimal investment strategies for bus-based transport under low to medium based passenger demand conditions* (Master's Dissertation). Pretoria: University of Pretoria. Available from: http://hdl.handle.net/2263/50840

Allen, H. 2013. *Africa's first full rapid bus system: The Rea Vaya bus system in Johannesburg*. South Africa.

African Association of Public Transport (UATP) congress and exhibition. 2014*. Proceedings held at Johannesburg, South Africa, 30 Sep–3 Oct 2014.* Conducted by UATP, the African Division of the International Union of Public Transport (UITP), Gautrain Management Agency (GMA) and the Department of Roads and Transport (DRT) of the province of Gauteng.

BRT Centre of Excellence. Available from http://www.brt.cl/

Bruun, E. 2005. Bus rapid transit and light rail: Comparing operating costs with a parametric cost model. *Journal of the Transportation Research Board*, 1927(1):11–21.

Bulman, A. & Valjarevic, D. 2016. *Operational analysis of the Rea Vaya BRT system for the City of Johannesburg.* South Africa.

Carrigan, A., King, R., Velasquez, J.M., Raifman, M.& Duduta, N. 2014. *Social environmental and economic impacts of BRT systems: Bus rapid transit case studies from around the world*. Washington: World resources institute.

Ceder, A. 2001. Operational objective functions in designing public transport routes. *Journal of Advanced Transportation*, 35:125–144.

Cervero, R. 2013. *Bus Rapid Transit: An efficient and competitive mode of public transport*. Working paper 2013–01. California, United States: Berkeley institute of urban and regional development.

Chitauka, F. & Vanderschuren, M. 2014. *An investigation into the performance of full BRT and partial bus priority strategies at intersections by micro-simulation modelling in a South African context.* Paper presented at the Southern Africa Transport Conference: Pretoria, South Africa.

City of Johannesburg, Institute for Transportation & Development Policy, Colleen McCaul & Associates, Namela Projects, Arcus Gibb, Osmand Lange & Novo Media. 2006. *Rea Vaya scoping study.* Johannesburg, South Africa.

City of Johannesburg. 2013. *Strategic integrated transport plan framework for the city of Johannesburg*. South Africa.

City of Johannesburg. 2017. *Integrated development plan*. Johannesburg, South Africa.

City of Johannesburg. n.d*. Rea Vaya BRT phase 1B business plan*. Johannesburg, South Africa.

Currie, G. 2005. The demand performance of bus rapid transit. *Journal of Public Transport*, 8: 41–55.

Del Mistro, R.F. & Aucamp, C.A. 2000. *Development of a public transport model*. Paper presented at the Southern Africa Transport Conference: Pretoria, South Africa.

Del Mistro. F. & Brunn. E. 2012. *Appropriate operating environments for Feeder-Trunk-Distributer or Direct road based public transport services in cities of developing countries*. Conference proceedings of the 31st South African Transport Conference (SATC): Pretoria, South Africa.

Deng, T. & Nelson, J. D. 2011. Recent developments in bus rapid transit: A review of the literature. *Transport Reviews Journal*, 31: 69–96.

Deng, T. & Nelson, J. D. 2013. Bus rapid transit implementation in Beijing: An evaluation of performance and impacts. *Research in Transportation Economics Journal*, 39:108–113.

Department of statistics South Africa. Available from http://www.statssa.gov.za/?p=11882

Ferro, P.S. & Behrens, R. 2015. From direct to trunk-and-feeder public transport services in the urban South territorial implications. *Journal of Transport and Land Use*, Vol. 8: 123–136.

Fielbaum, A., Jara-Díaz, S.R. & Gschwender, A. 2016. Optimal public transport networks for a general urban structure. *Transportation Research Part B*, 94: 298–313.

Gauteng Department of Roads and Transport. 2012. *Gauteng 25-year integrated transport master plan.* Johannesburg, South Africa.

Gilbert, A. 2008. Bus rapid transit: Is Transmilenio a miracle cure? *Transport Reviews Journal*, 28(4): 439–467.

Global BRT data. Available from https://brtdata.org/

Gschwender, A. 2005. *Improving the urban public transport in developing countries: The design of a new integrated system in Santiago, Chile*. 9th Conference on Competition and Ownership in Land Transport, September 7–11. Lisbon, Portugal.

Gschwender, A., Jara-Díaz, S.R. & Bravo, C. 2016. Feeder-trunk or direct lines? Economies of density, transfer costs and transit structure in an urban context. *Transportation Research Part A*, 88: 209–222.

Henderson, G., Kwong, P. & Adkins, H. n.d. Regularity indices for evaluating transit performance. *Transport Research Record, 1207:3-9*

Herrera, J.C., Muñoz.J.C., Hensher, D., Mulley. C., Li, Z.& Lindau.L.A. 2016. *Restructuring public transport through bus rapid transit: An international and interdisciplinary perspective.* Bristol, United Kingdom: Policy press. doi:10.1080/01944363.2017.1251284

Hidalgo, D. & Graftieaux, P. 2008. Bus rapid transit systems in Latin America and Asia: Results and difficulties in 11 cities. *Journal of the Transportation Research Board*, 2072:77–88.

Institute for Transport and Development Policy. 2017. The BRT planning guide. New York. Available from http://www.brtguide.org

Jara Díaz, S. & Gschwender, A. 2003. Towards a general microeconomic model for the operation of public transport. *Transport Reviews Journal*, 23(4): 453–469.

Jara-Díaz, S., Gschwender, A. & Ortega, M. 2012. Is public transport based on transfers optimal? A theoretical investigation. *Transportation Research Part B*, 46: 808–816.

Johansson, R., 2003. *Case study methodology*. Stockholm: Royal institute of technology.

Kathuria, A., Parida, M., & Sekhar, C. 2017. Route performance evaluation of a closed bus rapid transit system using GPS data. *Current Science*, 112(8), 1642–1652.

Kepaptsoglou, K. & Karlaftis, M. 2009. Transit routes networks design problem: Review. *Journal of Transportation Engineering*, Vol.135: 491–505.

Levinson, H. S., Zimmerman, S., Rutherford, S. C. & Eric, B. 2003. *Bus rapid transit implementation guidelines.* Washington: Transportation Research Board.

Lin. J. & Ruan. M. 2008. Probability-based bus headway regularity measure. IET Intelligent Transport Systems, Vol 3: 400-409. doi:10.1049/iet-its.2008.0088

Lindau, L.A., Moreira da Silva, C.A., Petzhold, G.& Facchini, D. 2014. *Global overview of BRT and bus corridors*. Transport Research Board 94th annual meeting: Washington, United States.

Mahadevia, D., Joshi, R., & Datey, A. 2012. *UNEP RISO centre report on low-carbon mobility in India and the challenges of social inclusion: Bus rapid transit (BRT) case studies in India*. New Delhi, India: Magnum custom publishing.

McCaul, C. & Ntuli, S. 2011. *Negotiating the deal to enable the first Rea Vaya bus operating company: Agreements, experiences, and lessons*. Johannesburg, South Africa.

Merkert, R., Mulley, C. & Hakim, M. 2017. Determinants of bus rapid transit (BRT) system revenue and effectiveness: A global benchmarking exercise. *Transportation Research Part A*,106: 75–88.

Peña, C. & Moreno, E. 2014. Delay at bus stops of Transmilenio transport system according to parameters measured “in situ”: Case study Bogotá-Colombia. *Procedia – Social and Behavioural Sciences*,160 (2014): 121–129

Peralta-Quiros, T. & Hernandez, C.R. 2016. *Balancing financial sustainability and affordability in public transport: The case of Bogota, Columbia*. Washington, United States: The World Bank Group.

Proboste, F., Muñoz, J.C. & Gschwender, A. 2020. *Comparing open and closed BRT networks in medium sized cities*. 22nd international symposiums for transportation and traffic theory: Santiago, Chile.

Salazar Ferro, P., Behrens, R. & Wilkinson, P. 2012. Hybrid urban transport systems in developing countries: Portents and prospects. *Research in Transportation Economics Journal*, Vol. 39(1): 121–132.

Show me South Africa. Available from https://showme.co.za/facts-about-south-africa/the-maps-of-south-africa/

Standish, B., Krogscheepers, C., Boting, A., Theron, J. & Swing, B. 2012. *Economic assessment of Rea Vaya Phase 1 A and 1B*. Johannesburg, South Africa.

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

Scorcia, H. & Munoz-Raskin, R. 2017. Why South African cities are different? Comparing Johannesburg Rea Vaya bus rapid transit system with its Latin American siblings. *Case Studies in Transport Policy Journal*, Vol. 7: 395–40. doi.10.1016/j.cstp.2019.01.010

Tiwari, G. 2014. *Bus Rapid Transit system: Metro on surface or high-performance bus system*. New Delhi, India: Indian institute of technology.

Transportation Research Board. 2016. *Highway Capacity Manual 6th Edition: A Guide for Multimodal Mobility Analysis*. Washington, DC: The National Academies Press. https://doi.org/10.17226/24798.

Velasquez, J.M., Tun, T.H., Hidalgo.D., Ramos, C., Guarda, P., Guo, Z. & Chen, X. 2017. *Bus rapid transit in China: A comparison of design features with international systems*. Washington, United States: World resources institute.

Vuchic, V.R. 2007. *Urban transit systems and technology*. New York, USA: John Wiley & Sons.

Wood, A. 2015. Multiple Temporalities of policy circulation: Gradual, repetitive, and delayed processes of BRT adoption in South African cities. *International Journal of Urban and Regional Research.* United Kingdom: Wiley-Blackwell publishing. doi:10.1111/ 1111/1468–2427.12216

Wright, L. & Hook, W. 2007. *Bus rapid transit planning guide*. New York: Institute of Transport and Development Policy.

Zhang, C. & Teng, J. 2013. Bus dwell time estimation and prediction: A study case in Shanghai-China. *Procedia-Social and Behavioural Sciences*, Vol. 96: 1329–1340. doi 10.1016/j.sbspro.2013.08.151

Zhang, M., Yen, B. T., Mulley, C., & Sipe, N. 2020. An investigation of the open-system Bus Rapid Transit (BRT) network and property values: The case of Brisbane, Australia. *Transportation Research Part A: Policy and Practice*, 134:16-34. doi.org/10.1016/j.tra.2020.01.021

APPENDIX A: STAKEHOLDER QUESTIONNAIRES

Questionnaire: City of Johannesburg

1. When was Rea Vaya implemented?
2. What was the reason behind the implementation of Rea Vaya?
3. Please explain the current operations
4. Please explain the relationship with the bus operators (management, service level agreement (SLA), etc.)
5. How is quality control being monitored by the city?
6. How are the fares structured?

Questionnaire: Operator

1. Please explain the relationship with the city (SLA, penalties, etc.)
2. What were was the main issues with regards to operations?
3. Please explain the resource structure
4. Please explain the operating costs
5. What are your views of direct and trunk-feeder BRT networks?

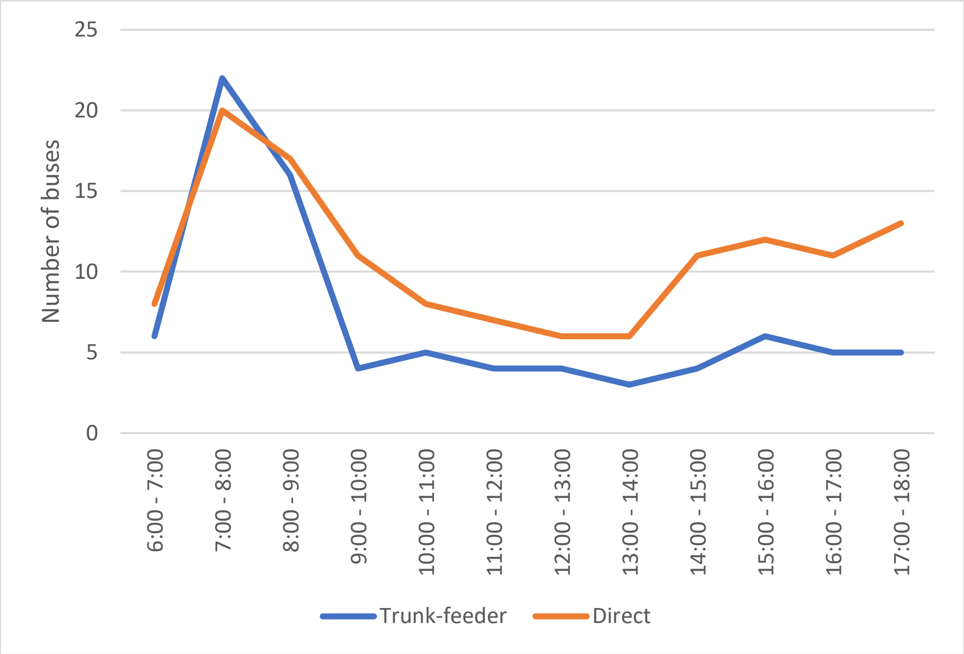
Questionnaire: Passenger

1. How often do you use Rea Vaya?
2. What are your reasons for using Rea Vaya?
3. What are your origin and destination points?
4. Please explain your experience with Rea Vaya. What are the main issues?
5. How do you feel about transfers?

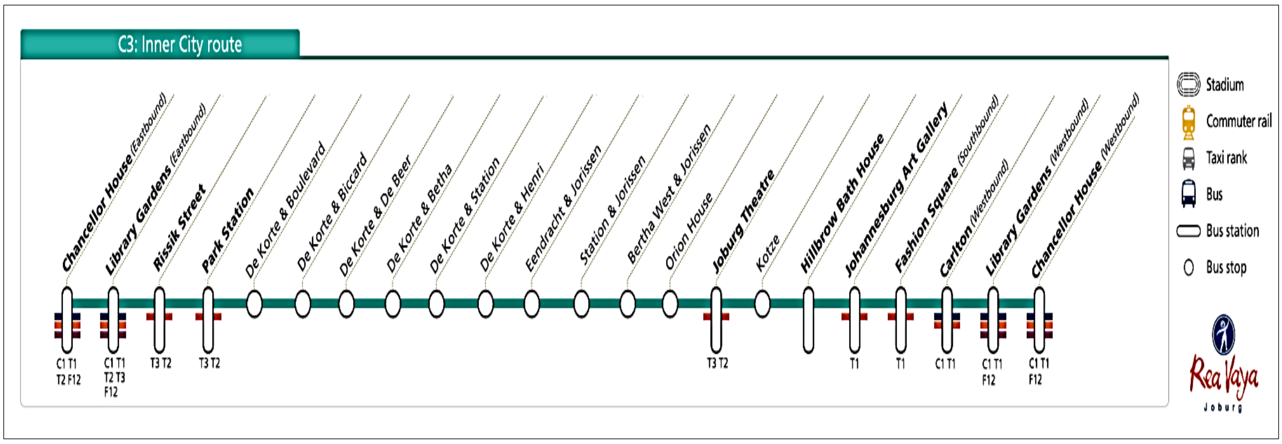
Questionnaire: Transport Specialists

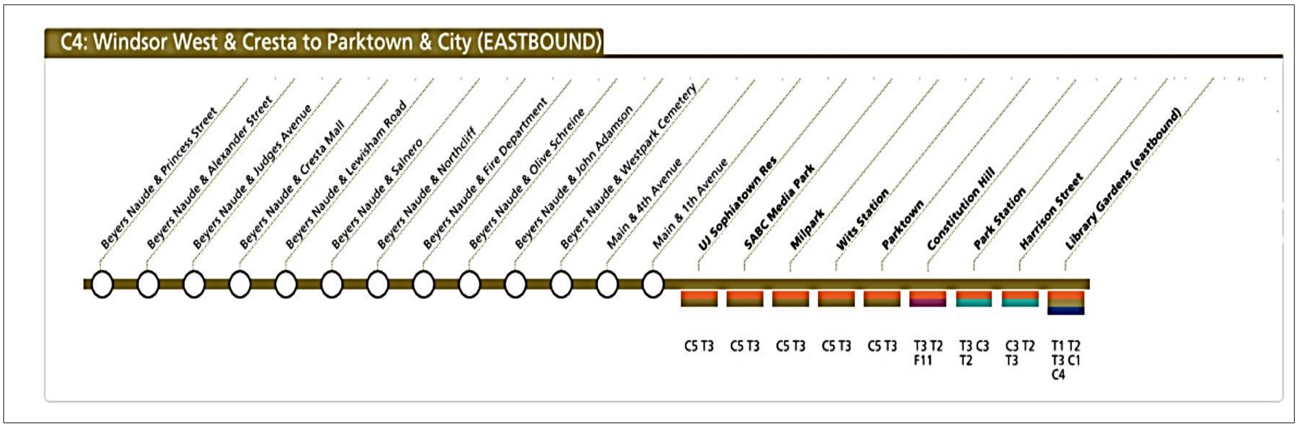
1. What is your view of BRT systems?
2. What is your experience with BRT systems?
3. What are direct and trunk-feeder BRT networks?
4. What are the main indicators that you recommend for a comparative analysis?

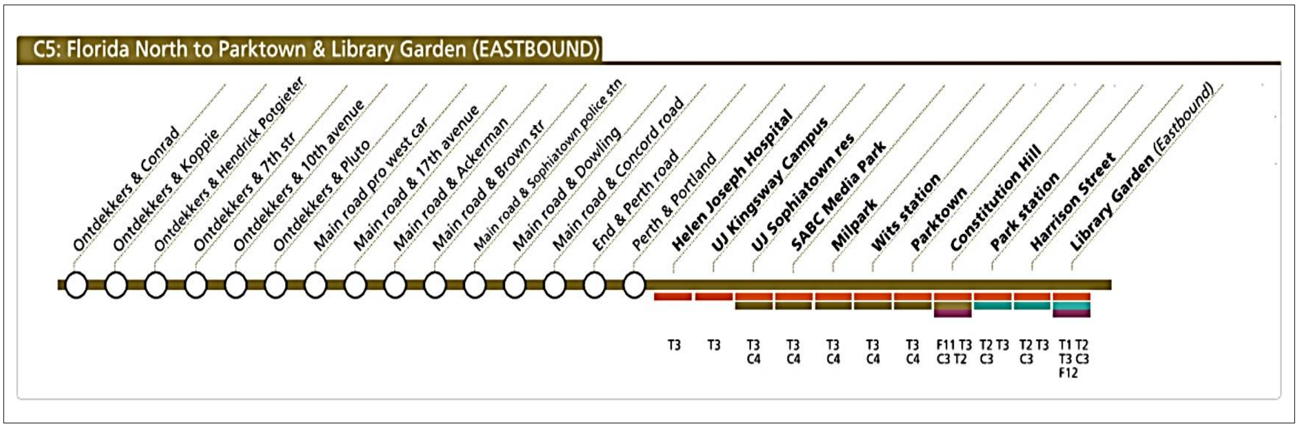
APPENDIX B: FREQUENCY GRAPHS: UJ SOPHIATOWN



APPENDIX C: ROUTE DIAGRAMS FOR C1, C4 AND C5







APPENDIX D: STATION SURVEY INSTRUMENT

Surveyors Name	Mashilwadi Rangata
Station Name	Library Gardens Eastbound
Date	04/04/2013

Bus service and type	Arrival time	Docking time(S)	Delays (S)	Number of passengers boarding
XT1	06:59	220	0	0
XT1	07:05	30	46	0
XT1	07:07	40	46	10
C1	07:07	17	0	10
C1	07:13	21	0	0
XT1	07:16	23	5	0
C1	07:17	21	32	0
XT1	07:17	22	34	0
C1	07:26	17	14	0
XT1	07:27	30	37	0
T1	07:28	28	0	3
T1	07:29	18	89	2
XT1	07:30	30	59	0
XT1	07:34	31	0	0
C4	07:36	49	460	70
C5	07:36	25	174	10
C1	07:43	28	25	5
C1	07:45	18	0	6
T1	07:48	15		0
C1	07:48	26	10	1
XT1	07:49	25	115	0
C5	07:51	20	62	15
XT1	07:51	18	0	4
XT1	07:54	24	0	0
XT1	07:57	15	427	0
C1	07:58	26	0	5
XT1	08:03	27	21	0
C1	08:09	22	0	0
T1	08:09	11	58	5
C1	08:10	25	0	0
T1	08:13	14	10	0
C1	08:13	15	23	0
T1	08:20	33	71	2
T1	08:21	32	0	1
T1	08:22	21	26	0
C1	08:27	20	25	2
C5	08:28	25	0	5
C1	08:30	26	30	1
C1	08:31	21	10	0
T1	08:33	30	20	2
T1	08:35	26	0	0
T1	08:36	15	0	0
C1	08:37	23	0	2

APPENDIX E: REA VAYA TICKETING DATA SAMPLE (RAW DATA)

Date	Time	Card No.	Media	No. Trips	Station / Stop On / Off	Station Stop Name / On Off	Ticket Failure?
2017/09/26	6:39:39	12042	Non-Emv-Media	1Trip(s)	9444	New Canada	TrxCheckIn
2017/09/26	7:23:46	12042	Non-Emv-Media	1Trip(s)	9035	Constitution Hill	TrxCheckOut
2017/09/27	7:02:24	12043	Non-Emv-Media	1Trip(s)	9444	New Canada	TrxCheckIn
2017/09/27	7:43:33	12043	Non-Emv-Media	1Trip(s)	9037	Constitution Hill	TrxCheckOut
2017/09/22	16:06:09	12044	Non-Emv-Media	1Trip(s)	9086	Joburg Theatre	TrxCheckIn
2017/09/22	16:47:39	12044	Non-Emv-Media	1Trip(s)	9447	New Canada	TrxCheckOut
2017/09/05	18:20:05	100986	Non-Emv-Media	1Trip(s)	8171	Ndaba & Almont Tech High	TrxCheckOut
2017/09/12	8:02:27	10079153	Non-Emv-Media	1Trip(s)	9019	Carlton Centre East	TrxCheckOutFailure
2017/09/12	8:02:28	10079153	Non-Emv-Media	1Trip(s)	9019	Carlton Centre East	TrxCheckOutFailure
2017/09/28	7:40:26	10110334	Non-Emv-Media	1Trip(s)	8054	Koma & Bolani	TrxCheckInFailure
2017/09/28	7:40:28	10110334	Non-Emv-Media	1Trip(s)	8054	Koma & Bolani	TrxCheckInFailure
2017/09/28	7:40:37	10110334	Non-Emv-Media	1Trip(s)	8054	Koma & Bolani	TrxCheckInFailure
2017/09/28	7:40:45	10110334	Non-Emv-Media	1Trip(s)	8054	Koma & Bolani	TrxCheckInFailure
2017/09/28	7:40:57	10110334	Non-Emv-Media	1Trip(s)	8055	Koma & Bolani	TrxCheckOut
2017/09/04	7:59:45	10186748	Non-Emv-Media	1Trip(s)	9421	UJ Sophiatown Res	TrxCheckOut
2017/09/04	8:01:33	10186748	Non-Emv-Media	1Trip(s)	9472	UJ Sophiatown Res	TrxCheckIn
2017/09/11	7:58:18	10186748	Non-Emv-Media	1Trip(s)	9421	UJ Sophiatown Res	TrxCheckOut
2017/09/11	8:02:44	10186748	Non-Emv-Media	1Trip(s)	9472	UJ Sophiatown Res	TrxCheckInFailure
2017/09/11	8:02:47	10186748	Non-Emv-Media	1Trip(s)	9472	UJ Sophiatown Res	TrxCheckIn
2017/09/13	7:54:30	10186748	Non-Emv-Media	1Trip(s)	9421	UJ Sophiatown Res	TrxCheckOut
2017/09/13	7:55:30	10186748	Non-Emv-Media	1Trip(s)	9472	UJ Sophiatown Res	TrxCheckIn
2017/09/14	20:37:37	10186748	Non-Emv-Media	1Trip(s)	9421	UJ Sophiatown Res	TrxCheckOut
2017/09/14	20:38:15	10186748	Non-Emv-Media	1Trip(s)	9472	UJ Sophiatown Res	TrxCheckIn
2017/09/26	7:41:25	10186748	Non-Emv-Media	1Trip(s)	9421	UJ Sophiatown Res	TrxCheckOut
2017/09/26	7:42:16	10186748	Non-Emv-Media	1Trip(s)	9472	UJ Sophiatown Res	TrxCheckIn
2017/09/28	7:40:45	10186748	Non-Emv-Media	1Trip(s)	9421	UJ Sophiatown Res	TrxCheckOut
2017/09/28	7:41:14	10186748	Non-Emv-Media	1Trip(s)	9472	UJ Sophiatown Res	TrxCheckIn
2017/09/14	20:37:24	10236640	Non-Emv-Media	1Trip(s)	9419	UJ Sophiatown Res	TrxCheckOutFailure
2017/09/20	14:08:00	10238925	Non-Emv-Media	1Trip(s)	9377	Harrison Station	TrxCheckOutFailure
2017/09/03	15:53:08	10341835	Non-Emv-Media	1Trip(s)	9414	SABC Media Park	TrxCheckIn
2017/09/22	18:50:19	10343358	Non-Emv-Media	1Trip(s)	8027	Super Saver	TrxCheckOut
2017/09/06	7:27:39	10463105	Non-Emv-Media	1Trip(s)	9419	UJ Sophiatown Res	TrxCheckOut
2017/09/06	7:28:57	10463105	Non-Emv-Media	1Trip(s)	9472	UJ Sophiatown Res	TrxCheckIn
2017/09/07	7:51:13	10463105	Non-Emv-Media	1Trip(s)	9419	UJ Sophiatown Res	TrxCheckOut
2017/09/07	7:55:22	10463105	Non-Emv-Media	1Trip(s)	9470	UJ Sophiatown Res	TrxCheckIn
2017/09/08	19:39:32	10463105	Non-Emv-Media	1Trip(s)	9419	UJ Sophiatown Res	TrxCheckOut
2017/09/08	19:40:15	10463105	Non-Emv-Media	1Trip(s)	9470	UJ Sophiatown Res	TrxCheckIn
2017/09/12	7:53:13	10463105	Non-Emv-Media	1Trip(s)	9421	UJ Sophiatown Res	TrxCheckOut
2017/09/12	7:54:03	10463105	Non-Emv-Media	1Trip(s)	9470	UJ Sophiatown Res	TrxCheckIn
2017/09/12	20:31:46	10463105	Non-Emv-Media	1Trip(s)	9421	UJ Sophiatown Res	TrxCheckOut
2017/09/12	20:32:29	10463105	Non-Emv-Media	1Trip(s)	9470	UJ Sophiatown Res	TrxCheckIn
2017/09/13	20:35:12	10463105	Non-Emv-Media	1Trip(s)	9419	UJ Sophiatown Res	TrxCheckOut
2017/09/13	20:36:18	10463105	Non-Emv-Media	1Trip(s)	9470	UJ Sophiatown Res	TrxCheckIn
2017/09/27	20:38:15	10463105	Non-Emv-Media	1Trip(s)	9419	UJ Sophiatown Res	TrxCheckOut
2017/09/27	20:39:32	10463105	Non-Emv-Media	1Trip(s)	9472	UJ Sophiatown Res	TrxCheckIn
2017/09/24	15:36:51	10466830	Non-Emv-Media	1Trip(s)	8180	Klipspruit Valley & Mtsintsi	TrxCheckInFailure
2017/09/30	15:02:55	10484406	Non-Emv-Media	1Trip(s)	9022	Carlton Centre West	TrxCheckInFailure
2017/09/14	6:47:49	10502996	Non-Emv-Media	1Trip(s)	9469	SABC Media Park	TrxCheckOut
2017/09/08	20:25:13	10514491	Non-Emv-Media	1Trip(s)	8180	Tsubaki & Bushingi	TrxCheckInFailure
2017/09/22	19:19:39	10528384	Non-Emv-Media	1Trip(s)	9347	Library Gardens East	TrxCheckOut
2017/09/22	19:22:53	10528384	Non-Emv-Media	1Trip(s)	9304	Library Gardens West	TrxCheckIn
2017/09/27	19:23:23	10528384	Non-Emv-Media	1Trip(s)	9349	Library Gardens East	TrxCheckOut
2017/09/27	19:25:45	10528384	Non-Emv-Media	1Trip(s)	9304	Library Gardens West	TrxCheckIn

APPENDIX F: OPERATING MODELS

	Route length	Trips per day	km per month	Bus purchase (R m)	No. of buses	Fuel price (R)	Fuel consumption (litres/ 100km)	Tyres (R/km)	Maintenance cost (R/km)	No. of shifts	No. of drivers	Wages (R)	Uniform (R)	Training (R)
T1	25,8	153	165791	5,2	43	16,5	62	0,59	14,66	3	129	9 170,00	141,72	159,44
T2	22,5	27	25515	5,2	13	16,5	62	0,59	14,66	3	39	9 170,00	141,72	159,44
T3	23	139	134274	5,2	39	16,5	62	0,59	14,66	3	117	9 170,00	141,72	159,44
C1	24,5	122	125538	4,3	26	16,5	55	0,52	11,91	3	78	9 170,00	141,72	159,44
C2	11,4	112	53626	4,3	7	16,5	55	0,52	11,91	3	21	9 170,00	141,72	159,44
C3	11	60	27720	4,3	4	16,5	55	0,52	11,91	3	12	9 170,00	141,72	159,44
C4	16	81	54432	4,3	12	16,5	55	0,52	11,91	3	36	9 170,00	141,72	159,44
C5	14,7	47	29018	4,3	5	16,5	55	0,52	11,91	3	15	9 170,00	141,72	159,44
C6	21	51	44982	4,3	15	16,5	55	0,52	11,91	3	45	9 170,00	141,72	159,44
F1	7,3	124	38018	4,3	4	16,5	55	0,52	11,91	3	12	9 170,00	141,72	159,44
F2	10,7	134	60220	4,3	12	16,5	55	0,52	11,91	3	36	9 170,00	141,72	159,44
F3	2,6	49	5351	4,3	2	16,5	55	0,52	11,91	3	6	9 170,00	141,72	159,44
F4	4,1	64	11021	4,3	2	16,5	55	0,52	11,91	3	6	9 170,00	141,72	159,44
F5	5,8	53	12911	4,3	2	16,5	55	0,52	11,91	3	6	9 170,00	141,72	159,44
F6	6,6	70	19404	4,3	3	16,5	55	0,52	11,91	3	9	9 170,00	141,72	159,44
F7	7	52	15288	4,3	2	16,5	55	0,52	11,91	3	6	9 170,00	141,72	159,44
F8	5,3	49	10907	4,3	1	16,5	55	0,52	11,91	3	3	9 170,00	141,72	159,44
F9	4	67	11256	4,3	2	16,5	55	0,52	11,91	3	6	9 170,00	141,72	159,44
F10	4	66	11088	4,3	1	16,5	55	0,52	11,91	3	3	9 170,00	141,72	159,44
F11	6,6	65	18018	4,3	4	16,5	55	0,52	11,91	3	12	9 170,00	141,72	159,44
F12	5,1	60	12852	4,3	3	16,5	55	0,52	11,91	3	9	9 170,00	141,72	159,44

	Fuel (R)	Maintenance (R)	**Tyres (R)**	**Insurance (R)**	Overheads (R)	Labour (R)	Leave (R)	Uniform (R)	UIF (R)	Training (R)	Vehicle repayment (R)	Cost per km (R/km)	Cost per passenger (R/pax)
T1	1 696 040	2 430 493	97 817	83 850	430 820	1 182 930	118 293	18 282	11 829	20 568	4 115 444	37	13
T2	261 018	374 050	15 054	25 350	67 547	357 630	35 763	5 527	3 576	6 218	1 244 204	45	11
T3	1 373 623	1 968 457	79 222	76 050	349 735	1 072 890	107 289	16 581	10 729	18 654	3 732 612	38	12
C1	1 139 257	1 495 158	65 280	41 925	274 162	715 260	71 526	11 054	7 153	12 436	2 058 134	31	18
C2	486 652	638 681	27 885	11 288	116 451	192 570	19 257	2 976	1 926	3 348	554 113	28	11
C3	251 559	330 145	14 414	6 450	60 257	110 040	11 004	1 701	1 100	1 913	316 636	28	23
C4	493 970	648 285	28 305	19 350	118 991	330 120	33 012	5 102	3 301	5 740	949 908	31	18
C5	263 337	345 602	15 089	8 063	63 209	137 550	13 755	2 126	1 376	2 392	395 795	29	17
C6	408 212	535 736	23 391	24 188	99 153	412 650	41 265	6 377	4 127	7 175	1 187 385	35	16
F1	345 017	452 799	19 770	6 450	82 404	110 040	11 004	1 701	1 100	1 913	316 636	27	9
F2	546 493	717 215	31 314	19 350	131 437	330 120	33 012	5 102	3 301	5 740	949 908	30	7
F3	48 559	63 728	2 782	3 225	11 829	55 020	5 502	850	550	957	158 318	36	2
F4	100 014	131 258	5 731	3 225	24 023	55 020	5 502	850	550	957	158 318	30	5
F5	117 166	153 768	6 714	3 225	28 087	55 020	5 502	850	550	957	158 318	29	6
F6	176 091	231 102	10 090	4 838	42 212	82 530	8 253	1 275	825	1 435	237 477	29	7
F7	138 739	182 080	7 950	3 225	33 199	55 020	5 502	850	550	957	158 318	28	6
F8	98 985	129 907	5 672	1 613	23 618	27 510	2 751	425	275	478	79 159	27	9
F9	102 148	134 059	5 853	3 225	24 529	55 020	5 502	850	550	957	158 318	30	4
F10	100 624	132 058	5 766	1 613	24 006	27 510	2 751	425	275	478	79 159	27	6
F11	163 513	214 594	9 369	6 450	39 393	110 040	11 004	1 701	1 100	1 913	316 636	31	9
F12	116 632	153 067	6 683	4 838	28 122	82 530	8 253	1 275	825	1 435	237 477	31	5