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DELAY MEASUREMENT AND PRIORITIZATION OF BRT AT SIGNALIZED INTERSECTION
(The Johannesburg Reavaya as a Case Study)

Dissertation submitted in compliance with the full requirements for the degree of
MASTER IN ENGINEERING

ELECTRICAL AND ELECTRONICS ENGINEERING SCIENCE

BY

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DATE: AUGUST 2017

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AUTHOR’S DECLARATION

I, AFOLABI OLUWATOBI JOSHUA declares that:

- The Work done in this dissertation is mine
- All sources referred to or used in this dissertation have been recognized and documented
- This dissertation has not been previously submitted in full or partial fulfillment of the requirements for an equivalent qualification at any other educational institution.

Author’s Signature                                                                                   Date: Aug. 2017
DEDICATION

I dedicate this work to the Almighty God for His great Love and faithfulness and also to my parents; Dr. and Mrs. M.O. Afolabi for their support all through this program.
ACKNOWLEDGEMENT.

I give all glory to the Almighty God who has made this project possible and for His endless provisions.

I would like to express my sincere appreciation to my supervisor; Prof. Bhekisipho Twala and co-supervisor; Prof. Felix N. Okonta for their outstanding support and supervision, fatherly advice, encouragement and great effort all through the course of the program.

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Mr. and Mrs. Tomiwa Osameyan- a ‘big’ thank you for your tremendous support, it is highly appreciated and to my colleagues Olayinka Abegunde, Abioye David Afolabi. Your contributions are unquantifiable. Finally, my heartfelt appreciation to my friends and ‘families’; Lade Osameyan, Jola Osameyan, Pastor Tosin, Kemi Adebowale. You all are worth keeping.
Bus Rapid Transit (BRT) is a transit system that makes use of modern and state of the art buses to deliver quick, comfortable and relatively cheap services usually at metro-level capacity.

This research focused on the BRT system used in Johannesburg called the “Reavaya” (which means ‘We are going’) which is also the BRT system that was used as a case study.

It is a common practice in other developed and developing countries that when a BRT system is built, a prioritized signal control at intersections that gives a right-of-way to the BRT is included on its corridors. However, as noticed at traffic intersections, the Reavaya buses were not prioritized at intersections leading to delay and more travel time of bus.

The project proposed a mathematical model that measured the control delay experienced by the bus at an un-prioritized signalized intersection. The model measured the extra delay caused by the bus deceleration on approaching the un-prioritized intersection and its subsequent acceleration back to its original travel speed. The result of the model proposed when used to measure delay was then compared with the results of the Canadian model and the on-site field measurement. The effect of complexity and geometry of intersections on delay was also studied using the models. A study on the effect of active prioritization of buses at signalized intersections was also conducted using SUMO (a simulation tool) and a comparison was drawn between traffic performance at un-prioritized intersections and traffic performance at prioritized intersections.

From the result, it was found that the mathematical model proposed measured more accurately the overall delay experienced by a bus at a signalized intersection when compared to other delay models and the DT (delay time) component of the proposed model was very close to the on-site field measurement value (with as little as 1% difference at some intersections). It was also found that the use of active prioritization on the Reavaya corridors has great benefits. For the corridor simulated, there was about 68% reduction of waiting time at intersections, 13% reduction in CO₂ emission, 15% reduction in NOx and PMx, 12% reduction in HC and 17% reduction in CO while having little impact on the travel time of the general traffic. For all of the edges considered, the maximum increase in the general traffic travel time, occupancy and waiting time at any intersection were 16%, 20%, 19% and 15% respectively and a maximum of 15% reduction in the speed the vehicle would need to cross over any of the intersection considered.

Therefore active prioritization technique is a suitable priority technique that could be deployed.
# TABLE OF CONTENTS

- AUTHOR’S DECLARATION ................................................................. ii
- DEDICATION .................................................................................. iii
- ACKNOWLEDGEMENT ................................................................. iv
- ABSTRACT ...................................................................................... v
- TABLE OF CONTENTS ................................................................... vi
- ABBREVIATION ................................................................................ x
- LIST OF FIGURES ............................................................................ xii
- LIST OF TABLES ............................................................................. xvi
- GLOSSARY OF TERMS ................................................................. xvii

## CHAPTER 1: INTRODUCTION ......................................................... 1

- 1.1 THEORETICAL BACKGROUND ................................................ 1
- 1.2 PROBLEM STATEMENT .......................................................... 4
- 1.3 MOTIVATION OF RESEARCH ................................................ 4
- 1.4 AIM OF THE RESEARCH ........................................................ 4
- 1.5 OBJECTIVES OF THE RESEARCH ......................................... 4
- 1.6 HYPOTHESIS ............................................................................ 5
- 1.7 METHODOLOGY ....................................................................... 5
- 1.8 DELIMITATIONS ....................................................................... 6
- 1.9 SIGNIFICANCE OF THE RESEARCH ....................................... 6
- 1.10 ORGANIZATION OF DISSERTATION ..................................... 6
CHAPTER 2: LITERATURE REVIEW ................................................................. 7

2.1 INTRODUCTION .......................................................................................... 7

2.2 UN-SIGNALIZED INTERSECTION CHALLENGES .................................... 7

2.3 SOME BENEFITS OF SIGNALIZED INTERSECTIONS ............................... 9

2.4 DELAY MODELS FOR SIGNALIZED INTERSECTIONS .............................. 10

2.4.1 WEBSTER’S DELAY MODEL ................................................................. 11

2.4.2 OTHER DELAY MODELS ........................................................................ 16

2.5 STOPPING SIGHT DISTANCE ................................................................. 18

2.5.1 STOP SIGHT DISTANCE AND HORIZONTAL CURVES ...................... 20

2.6 TYPES OF INTERSECTIONS AND COMPLEXITY ................................... 21

2.6.1 GRADE SEPARATED INTERSECTION OR INTERCHANGE ............... 22

2.6.2 AT-GRADE INTERSECTIONS ............................................................... 25

2.6.3 COMPLEXITY OF INTERSECTIONS ..................................................... 27

2.7 EFFECTS OF INTERSECTION COMPLEXITY AND GEOMETRY ............ 28

2.7.1 EFFECT OF NUMBER OF INTERSECTION-LEGS ON DELAY ........... 29

2.7.2 EFFECT OF SKEW AT INTERSECTIONS ................................................ 29

2.7.3 EFFECT OF HORIZONTAL AND VERTICAL CURVES

ON DELAY AT INTERSECTIONS ................................................................. 31

2.8 TRANSIT SIGNAL PRIORITY SYSTEM ................................................... 32

2.8.1 BUS SIGNAL PRIORITY TREATMENTS .............................................. 33

2.8.2 TECHNIQUES OF TSP SYSTEMS ......................................................... 34

2.8.3 VEHICLE DETECTION SYSTEM .......................................................... 35

2.9 SIMULATION IN SUMO ............................................................................ 38

2.9.1 SUMO CAR FOLLOWING MODELS .................................................... 39
2.9.2 SUMO LANE-CHANGING MODELS .................................................................40

2.10 SUMMARY .................................................................................................42

CHAPTER 3: METHODOLOGY ........................................................................43

3.1 INTRODUCTION ..........................................................................................43

3.2 TOTAL TRAVEL TIME MEASUREMENT ....................................................43

3.3 PROPOSED DELAY MODEL FOR BUS ONLY ROUTE ..................................46

3.3.1 STOP SIGHT TIME .................................................................................46

3.3.2 DELAY MEASURED WHEN BUS IS FULLY STOPPED (DT) ....................48

3.3.3 ACCELERATION TIME (AT) .................................................................50

3.4 BUS STATION LOCATION EFFECT ON MODEL .......................................52

3.4.1 FAR SIDE BUS STATION .................................................................52

3.4.2 NEAR SIDE BUS STATION .................................................................53

3.5 DATA COLLECTION ...................................................................................55

3.5.1 FIELD WORK ......................................................................................61

3.6 MODELLING IN SUMO ..............................................................................62

3.6.1 DATA COLLECTION DETAILS AND SCOPE .......................................65

3.6.2 DATA VALIDATION ...............................................................................66

3.7 SUMMARY ..................................................................................................66

CHAPTER 4: RESULT AND DISCUSSION .......................................................67

4.1 INTRODUCTION ..........................................................................................67

4.2 TRAVEL TIME ELEMENTS OF REAVAYA

BUS RAPID TRANSIT EXAMINED .................................................................67

4.2.1 TRAVEL TIME ELEMENTS ANALYZED

BY PERIOD OF THE DAY ..............................................................................68

4.2.2 TRAVEL TIME ELEMENTS ANALYZED
BY DIRECTION OF TRAVEL .................................................................70

4.3 COMPARISON OF THE REAVAYA TRAVEL TIME WITH
OTHER BRTs ..........................................................................................72

4.4 OBSERVED EFFECT OF PLATOONING ..............................................72

4.5 COMPARISON OF DELAY MEASUREMENT METHODS .......................74

4.6 MINIMUM SPACING OF INTERSECTIONS ALONG
BUS RAPID TRANSIT LANES ...............................................................78

4.7 ANALYSIS OF RESULTS TO SHOW THE EFFECT OF COMPLEXITY
AND GEOMETRY OF INTERSECTIONS ON DELAY ............................79

4.7.1 EFFECT OF NUMBER OF LEGS OF INTERSECTION ON DELAY .......79

4.7.2 EFFECT OF SKEW AT INTERSECTIONS ON DELAY .....................80

4.7.3 EFFECT OF NUMBER OF LEGS OF INTERSECTION
ON DELAY DURING OFF-PEAK PERIODS ........................................81

4.7.4 EFFECT OF SKEW AT INTERSECTIONS ON DELAY
DURING OFF-PEAK PERIODS ............................................................82

4.8 SUMO SIMULATION RESULTS ..........................................................84

4.8.1 RESULT SHOWING EFFECT OF PRIORITIZATION
ON BUS OPERATIONS ........................................................................84

4.8.2 RESULT SHOWING EFFECT OF PRIORITIZATION
ON ROAD NETWORK .................................................................87

4.9 PRIORITIZATION OF SIGNALS DISCUSSION ........................................92

4.9.1 BUS CORRIDOR POSITION .........................................................92

4.9.2 NUMBER OF SIGNALIZED INTERSECTION PER KILOMETER ...........94

4.10 PROPOSED PRIORITIZATION TECNIQUE ........................................94

4.11 SUMMARY ..................................................................................94

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS ..........................95

5.1 INTRODUCTION: ...........................................................................95

5.2 CONCLUSION ...............................................................................95

5.3 RECOMMENDATION .....................................................................96

REFERENCES ..................................................................................97

APPENDIX A ......................................................................................106

APPENDIX B ......................................................................................108
ABBREVIATION

AASHTO - American Association of State Highway and Transportation Officials

ALPR – Automatic License Plate Recognition

AVL- Automatic Vehicle Location

BRT- Bus Rapid Transit

CO₂ – Carbon (IV) Oxide gas.

CO – Carbon (II) Oxide gas

EMTRAC - Evansville Museum Transportation Center

FHWA – Federal Highway Administration

FDOA – Frequency Difference of Arrival

HBEFA – Handbook Emission Factors for All current vehicle categories

HC – Hydro Carbons.

HCM – Highway Capacity Manual

HOV- High Occupancy Vehicle

HPW – High performance Waveform

HV- Heavy Vehicle

LOS – Level of Service

MOE – Measure of Effectiveness
NOx – Nitrogen Oxides
PCU- Passenger Car Unit
PMx – Particulate Matter
RD – Random Delay
RF – Radio Frequency
RIT – Return in Transit
ROW – Right of Way
SSD – Stop Sight Distance
SUMO – Simulation of Urban Mobility
TCRP - Transit Co-operative Research Program
TOD – Total Overflow Delay
TRANSYT- Traffic Network Study Tool
TriMet - Tri-County Metropolitan Transportation
TSP- Transit Signal Priority
UD – Uniform Delay
UTC – Uniform Traffic Control System
U-TDOA - Uplink-Time Difference of Arrival
VISSIM - Verkehr In Städten - SIMulationsmodell
WSDOT – Washington State Department of Transport.
LIST OF FIGURES

Figure 1.1. A dedicated ROW [3] ................................................................. 2

Figure 1.2. Active Priority Concepts [7] ....................................................... 3

Figure 2.1. Illustration of Webster’s Uniform delay model [31] ...................... 11

Figure 2.2. Illustration of Continuous Overflow delay model [31] .................... 14

Figure 2.3. Derivation of the Overflow delay model [31] ............................... 14

Figure 2.4. Overflow delay between time T1 and T2 [31] ............................... 15

Figure 2.5. Comparison of Overflow and random delay model [31] ................. 16

Figure 2.6. Horizontal Curve along a highway [37] .................................... 20

Figure 2.7. Horizontal sight line offset [38] ............................................... 20

Figure 2.8. An overpass interchange [39] .................................................... 22

Figure 2.9. An underpass interchange [40] ............................................... 23

Figure 2.10. Diamond interchange [41] ..................................................... 23

Figure 2.11. Trumpet interchange [42] ....................................................... 24

Figure 2.12. Cloverleaf interchange [43] .................................................... 24

Figure 2.13. Partial Cloverleaf interchange [44] ........................................ 25

Figure 2.14. Directional interchange [45] .................................................. 25

Figure 2.15. Roundabout intersection [46] ................................................ 26
Figure 2.16. Flared intersection [46] .................................................................26

Figure 2.17. Channelized intersection [47] ..........................................................27

Figure 2.18. Simple intersection [48] .................................................................27

Figure 2.19. Three approaches intersection [49] ....................................................28

Figure 2.20. Four approaches intersection [50] ....................................................28

Figure 2.21. Multi approaches intersections [51] ...............................................28

Figure 2.22. Conflicting movements in three and four legs intersections ...............29

Figure 2.23. Difference in intersection area for: A. perpendicular intersection

and B. skewed intersection ..............................................................................31

Figure 2.24. Schematic flow of TSP used in Portland [63] ....................................32

Figure 2.25. Representation of traffic signal prioritization process [67] .................35

Figure 2.26. Bus detection using Transponder and tag system [73] .......................36

Figure 3.1. Field Measurement chat .................................................................44

Figure 3.2 Bus stations and route along which travel measurement was taken ..........45

Figure 3.3. An illustration of the components of SST .........................................48

Figure 3.4. An illustration of the stopped delay at signalized intersection ...............48

Figure 3.5. An illustration of the total delay experienced by bus at a signalized intersection ....51

Figure 3.6. Graphical representation of the cycle a bus went through at the sight
of a stop signal. .................................................................52

Figure 3.7. Graphical representation of the cycle a bus went through at the sight

of a stop signal when the bus station was far side. ........................................53

Figure 3.8. Graphical representation of the cycle a bus went through at the sight

of a stop signal when the bus station was near side ......................................54

Figure 3.9. University Road/ Kingsway Avenue .............................................56

Figure 3.10. Stanley Avenue/ Annet Road intersection. .................................56

Figure 3.11. Perth Road/ Lewes Road Intersection ........................................57

Figure 3.12. Harmony Street/ Main Road Intersection ......................................57

Figure 3.13. Hay Avenue/ Harmony Street Intersection ....................................58

Figure 3.14. New Canada Road/ Main Reef Road. ...........................................58

Figure 3.15. Empire Road/ Jan Smuts Avenue Intersection ...............................59

Figure 3.16. Empire Road/ Victoria Avenue Intersection .................................59

Figure 3.17. Rissik/ Smit and Rissik/ Wolmarans Intersection ..........................60

Figure 3.18. The BRT corridor Network Diagram as generated from SUMO .................63

Figure 3.19. The BRT corridor selected as generated from SUMO during simulations ........63

Figure 3.20. The BRT corridor showing the bus-only lanes and the adjacent lanes ........64

Figure 4.1 How the travel time elements add up to make the total time ......................67
Figure 4.2 Mean value of the travel time elements for different times of the day ......................68

Figure 4.3 Comparison of Red-light running cases during the peak and off peak periods..........69

Figure 4.4 A case of Red-light running .................................................................69

Figure 4.5 Average travel time elements analyzed by direction of travel ............................70

Figure 4.6 Travel time analyzed by direction of travel and also by the time periods of the day....71

Figure 4.7 Bus platooning at a signalized intersection .................................................73

Figure 4.8 Bus platooning at a bus station ...............................................................73

Figure 4.9 Comparison of DT value and the field measurement ......................................75

Figure 4.10 Comparison of delay values as measured by the proposed model .......................76

Figure 4.11 Comparison of field measurement and Canadian model .................................77

Figure 4.12 Comparison of Canadian model, field measurement and the proposed model ................78

Figure 4.13 Comparison between average delays experienced at three-leg intersections and at four-leg intersections .................................79

Figure 4.14 Comparison between average delays experienced at three-leg intersections and at three-leg skewed intersections .................................80

Figure 4.15 Comparison between average delays experienced at four-leg intersections and at four-leg skewed intersections .................................81
Figure 4.16 Comparison between average delays experienced at three-leg intersections and at four-leg intersections for off-peak periods…………………..82

Figure 4.17 Comparison between average delays experienced at three-leg intersections and at three-leg skewed intersections for off-peak periods.............83

Figure 4.18 Comparison between average delays experienced at four-leg intersections and at four-leg skewed intersections for off-peak periods.............83

Figure 4.19 Comparison of average speed of bus along corridor .................................................................85

Figure 4.20 Comparison of waiting time at intersections.................................................................85

Figure 4.21 Comparison of fuel consumption rate by the buses .........................................................86

Figure 4.22 Comparison of emissions (CO2, CO, HC, NOx, PMx) from the buses .................................86

Figure 4.23 Edges 1,2,3,4 from 2 different intersections .................................................................88

Figure 4.24 Edges 5,6,7,8 from 2 different intersections .................................................................88

Figure 4.25 Edges 9,10,11,12 and 13 from 2 different intersections .........................................................89

Figure 4.26 Edge 14..................................................................................................................................89

Figure 4.27 Bus way completely separated from the general traffic .........................................................93

Figure 4.28 Bus way at the center of the general traffic .................................................................93
LIST OF TABLES

Table 2.1. Calibration Parameters Value for the Australian, Canadian, HCM, Akcelic and Transyt 8 delay model [24] ........................................ 18

Table 2.2. AASHTO Recommendations for coefficient of static friction [25] .........................19

Table 2.3. Bus signal priority system [44] ...........................................................................33

Table 2.4. Advantages and Limitations of various detection technologies [50] ......................37

Table 3.1. Intersections showing the allocated green time portion. ......................................61

Table 3.2. Data used for the modelling and the sources of the data ..........................................66

Table 4.1 Mean values of travel time elements for different time of the day ..........................68

Table 4.2 Bosmont-station bound mean values of travel time elements for different time of the day .................................................................71

Table 4.3 Park-station bound mean values of travel time elements for different time of the day ..................................................................................72

Table 4.4 Average delay experienced by a bus at signalized intersection measured by using the field measurement technique, the Canadian model and the proposed model .................................................................74

Table 4.5 Network Performance measurement and comparison between prioritized intersections and un-prioritized intersections ........................................90
GLOSSARY OF TERMS

A

- **Acceleration**: the rate at which velocity of vehicles changes per unit time. Its’ unit is taken to be \( \text{m/s}^2 \)
- **Acceleration time**: the time measured in seconds during which the bus increases its speed (it could be from rest) till it reaches its normal cruise speed along the bus corridor.
- **Access point**: this refers to private or public roads, driveways, intersections, ramps or paths which is linked to another public road.
- **Actual Green**: This is the green phase as displayed by the traffic signal at a signalized intersection.
- **Afternoon Peak**: the time in the afternoon when traffic congestion on roads and demand for public transport services is at its’ zenith.
- **Analytical Models**: These are mathematical models whose solution is used to describe changes in a system.
- **Artery**: This refers to a very important route or lane in a network of roads.
- **Articulated bus**: these are buses which allows passengers to walk from one of its end to the other but it is bent at the middle to allow the bus to navigate around corners. It is usually longer than the regular bus. Typically, articulated buses are about 18meters long.
- **Automatic Vehicle location**: This is a technology which is used to determine and transmit the geographical location of a bus.
- **Auxiliary Lane**: An auxiliary lane is defined as the portion of the roadway adjoining the travelled way for speed change, turning, weaving, truck climbing, maneuvering of entering and leaving traffic, and other purposes supplementary to through-traffic movement.

B

- **Braking**: This refers to the process of slowing down, stopping completely or keeping stationary a vehicle, a wheel or a shaft.
- **Bus**: a large and high occupancy vehicle which carry commuters by road and is usually operated on a fix route and for a fare. They are usually about 11-14 meters long.
• **Bus Arrivals**: This refers to the number of buses which gets to an intersection within a specified period of time.

• **Bus Corridor**: This refers to a section of road or network that is served by a bus route which has dedicated lanes. It has a minimum standard length of 3 kilometers.

• **Bus departures**: This refers to the number of buses that leaves an intersection within a specified period of time.

• **Bus Frequency**: This is the number of buses that arrives at the bus station in one hour divided by 60.

• **Bus Lane**: it refers to a part of the road that has been marked off or signed with painted lines to be used by buses only.

• **Bus station**: it is a structure (covered or uncovered) where buses stop so as to allow passengers or commuters to board or alight from a bus.

• **Bus only route**: same as bus lane

• **Calibration**: This is the setting or correcting of a measuring device or base level, usually by adjusting it to match or conform to a dependably known and unvarying measure.

• **Calibration Parameters**: these are variables in a mathematical model whose values are adjusted to match and conform to a known measure.

• **Capacity of lane**: this is defined to be the maximum howdy rate at which persons or vehicles can be reasonably expected to traverse a point or a uniform segment of a lane or roadway during a given time period, under prevailing roadway, traffic and control conditions.

• **Coefficient of friction**: This is a term that is used to refer to the relationship that exist between the force of friction between two objects and the normal reaction between the objects in focus.

• **Commuter**: a term used to refer to a person that travels some distance to work using the bus on a regular basis.

• **Control delay**: This is the delay experienced by a bus at a signalized intersection as a result of the type of control (which is the use of traffic lights) at the intersection.

• **Control Signals**: A set of light that comes on at a definite pre-programmed time that represents a control command and directing a driver as to what to do at a particular intersection.

• **Cumulative Bus**: The total number of bus arrivals and departures at a particular intersection over a specified period of time.
- **Curb side**: this refers to the side of a pavement or street which is bordered by a concrete or metal rail along the edge of that street.

- **Cycle failure**: a situation in a signal cycle in which there is still an existing queue of vehicles after the end of a phase.

**D**

- **Dedicated Lane**: same as bus lane.

- **Degree of Saturation**: The degree of saturation usually expressed in percentage is a ratio of demand to capacity on each approach of the junction, with a value of 100% meaning that demand and capacity are equal and no further traffic is able to progress through the junction.

- **Delay model**: a set of mathematical equations whose solution describes the delay experienced by buses along the bus only route (as used in this thesis).

- **Delay Optimization**: this refers to the set of actions geared towards using the available resources to reduce delay at intersections and improving the overall traffic condition at the intersection.

- **Design speed**: this is the speed that was used during the road design to determine the geometric features of the road. It is different from the posted speed of the road and the speed with which a driver would rather travel along the road.

- **Detectors**: This is a device that has been designed to pick up the presence of a vehicle or bus.

- **Downstream**: This refers to direction of flow of traffic into an intersection.

- **Dwell time**: This is the time spent by a bus at a bus station. It includes the time it takes for the passengers to board and alight from the bus.

**E**

- **Edge**: This is used to refer to combination of lanes on a roadway e.g. a simple two-way road has two edges but may have more than two lanes.

- **Effective green**: This is a term that refers to the time of the actual green and the amber or yellow time which is usually treated as green by the drivers.
• **Facility Speed**: This is the posted speed along the road for drivers. It is also the speed limit for a particular road section.

• **Far side Intersection**: As used in this theses refers to an intersection located some few meters after the bus station.

• **Fare Collection system**: A system put in place to help in the automation of the ticketing system of a public transportation network.

• **Feeder roads**: a road that acts as a secondary road to bring traffic to a more important road.

• **Flow Period**: The period of time or length of time during which traffic flows (arrivals or departures) are examined.

• **Free way**: an express highway with no intersections, usually having traffic routed on and off by means of a cloverleaf.

• **Fuel consumption**: This refers to the amount of fuel used by a vehicle (a bus) to travel a known distance at a particular speed.

• **Gap**: this is used to refer to the time measured in seconds for the second of two successive vehicles to reach the starting point of the front bumper of the first.

• **Gap-acceptance**: this refers to the process involved for a minor street vehicle to accept an available gap to maneuver.

• **Gradient**: Ratio of the vertical distance to the actual distance along the road. It is usually quoted in percentages.

• **Green Phase**: same as phase.

• **Green Time**: the length of time usually in seconds of the green signal for a particular direction and movement at a signalized intersection.

• **Headway**: the time in seconds between two successive buses as they pass an intersection measured from the same common feature of both buses.
• **Heavy vehicle**: This refers to any vehicle which has more than four wheels touching the road as it cruises along.

• **High Occupancy vehicle**: this usually include buses, taxis and car pools especially when they run on reserved lanes. They are vehicles which has a defined minimum numbers of occupants.

• **High way**: This refers to a main road especially one that connects major cities and towns.

• **Highway capacity manual**: a publication of the Transportation Research Board of the national academies of science in the United States.

• **Horizontal curve**: This is an important transition element in geometry design of highways that gives a transition between two tangents strip of road way, allowing a vehicle to negotiate a turn at a gradual rate rather than a sharp cut.

I

• **Infinite**: a term which is used to refer to a value which is impossible to measure or calculate.

• **Infrared**: this is a term that refers to energy in the region of the electromagnetic radiation spectrum at wavelength longer than those of the visible light but shorter than those of the radio waves.

• **In-Phase**: two or more movements in an intersection (or more) are said to be in phase if they receive the right of way or a green phase at the same time simultaneously.

• **Intersection**: this refers to a point where two or more roads meet. Also commonly referred to as a road junction.

• **Interchange**: an interchange is a type of road intersection that employs the use of grade separation and one or more ramps to permit traffic on at least one highway to pass through the junction without directly crossing any other traffic stream.

K

• **Kinetic Energy**: This is the energy possessed by a body due to its motion. it is equal to the product of half of its mass and square of its velocity.
Lane: This refers to a part of a roadway which has been designated for use by a single line of vehicles to control and guide drivers and also to reduce traffic conflicts.

Level of Service: This refers to a qualitative measure that describes the operational conditions within a traffic stream, based on service measures such as speed, travel time, delay and freedom to maneuver, traffic interruptions, comfort and convenience.

License plate recognition: This refers to any technology that uses optical character recognition on images to read vehicle registration plates.

Loop: this is a shape produced by a curve that bends round and crosses itself.

Maneuver: this refers to a movement or series of movement that requires a level of skill and care.

Mass: A property of matter that measures the resistance of the matter to acceleration. It is measured in kilograms.

Measure of Effectiveness: a quantitative parameter indicating the performance of a transportation facility or service.

Minor road: a road controlled by stop signs at a two-way stop–controlled intersection.

Morning peak: the time in the morning when traffic congestion on roads and demand for public transport services is at its’ zenith.

Near side Intersection: as used in this theses refers to an intersection located just some few meters before the bus station.

Network: this is a system of interconnecting lines or points that represents a system of streets or roads for a given area.
- **Off-peak period**: This is a period of time typically after the business hours when public transport services demand and traffic congestion on roads are in their lowest.
- **Off-board**: this is a term that refers to any activity that is required by a commuter or passenger to undertake before he or she can board the bus.
- **Off-set**: this refers to the amount or distance by which something (an obstruction) is out of line.
- **Optics**: a study that deals with the generation and the use of electromagnetic radiation, the properties of the radiation and the interaction of that radiation with matter especially its manipulation and control.
- **Overflow delay**: extra delay experienced by vehicles as a result of queued vehicles left over from a green phase at a signalized intersection.

- **Peak period**: the time in the day (morning, afternoon or evening) when traffic congestion on roads and demand for public transport services is at its’ zenith
- **Perception time**: This is the time it takes a driver to detect or notice an object in the driving environment and also to comprehend its significance.
- **Phase**: this refers to the part of a signal cycle allocated to any combination of traffic movements receiving the right-of-way simultaneously during one or more intervals.
- **Phase advancement**: this is a term that is used to refer to the act of allowing a green phase earlier than its normal sequence so as to allow for a lane prioritization.
- **Phase extension**: this is a term that is used to refer to the act of making longer than its normal period a green phase so as to allow for a lane prioritization.
- **Platform**: a raised level surface that allows passengers to stand.
- **Power to weigh ratio**: this is a term that measures the power of a vehicle (bus) against its weight. It is a calculation commonly applied to engines and mobile power sources to enable the comparison of one unit or design to another.
- **Prioritized Intersection**: this is a signalized intersection that gives a right-of-way to a designated lane and thereby reducing stoppage or delay along that lane at such intersection.
R

- **Radio frequency**: this is a frequency or band of frequencies in the range $10^4$ to $10^{12}$ Hz and is suitable for use in telecommunications and control.
- **Random delay**: this is a portion of the delay model that compensates for random arrival of vehicles at an intersection.
- **Reaction time**: the time taken for a bus driver to respond to a strange object or otherwise unexpected change in the driving environment.
- **Real time**: this is a term relating to a system in which input data is processed within milliseconds so that it is available virtually immediately as feedback.
- **Red Phase**: same as red time
- **Red time**: the period expressed in seconds in the signal cycle during which for a given phase or lane group the signal is red.
- **Reserved ways**: a lane or set of lanes set apart for some exact use or purposes.
- **Right-of-way**: the direct access given to any combination of traffic movements at an intersection.

S

- **Saturation flow rate**: this is a term that refers to the equivalent hourly rate at which previously queued vehicles can transverse an intersection approach under prevailing conditions with an assumption that the green signal is available at all times and no lost times are experienced, in vehicles per hour or in vehicles per hour per lane.
- **Schematic**: a diagram or some other type of representation which is symbolic and has been simplified for ease of understanding.
- **Side road**: same as minor road
- **Sight line**: this is a hypothetical line that extend from an observer’s eye to a viewed object or road.
- **Signal cycle**: this is a term that refers to the complete sequence of signal indications.
- **Signal priority system**: this a set of system put together to achieve prioritization of lane(s) at a signalized intersection.
• **Simulation**: This is an experiment of traffic events on a transportation facility or system carried out using a computer program.

• **Stop line**: This is a road marking indicating to a driver where he is expected to stop at an intersection.

• **Stop sign**: It is a traffic sign placed ahead to notify drivers that they must make sure no cars are coming and slow down before proceeding.

• **Stop-sight-time**: This refers to the time it takes a driver to decelerate from its travel speed to a stop or a much less speed at an intersection.

**T**

• **Thrust**: This is the force applied on a surface or body in a direction perpendicular or normal to the surface or body.

• **Traffic**: This is a term that refers to the movement of vehicles, passengers, cyclists and pedestrians in an area or along a route.

• **Traffic flow**: The quantity of vehicles (measured in PCUs) or pedestrians arriving at a particular point on a link (e.g. a stop line) or passing a particular point, per unit time.

• **Traffic signals**: They are traffic control mechanisms which are electrically operated that give indication to pedestrians, cyclists and drivers allowing them to advance or impede their travels by assigning ROW to each approach and movement at different period.

• **Traffic volume**: This refers to the number of persons or vehicles that passes a point on a lane, road way or other traffic-way during some time interval usually 1 hour expressed in vehicles or persons per hour.

• **Transit**: The movement of passengers and goods along a corridor.

• **Transponder**: A device that has been designed to receive a radio signal and automatically transmit a different signal.

• **Travel speed**: The average speed measured in kilometres/hour of a traffic stream which is obtained by dividing the length of the traffic corridor by the average travel time of the vehicles that travels along this corridor.

• **Travel time**: The average time measured in seconds spent by vehicles that travel along a corridor and including the delay experienced at intersections.

• **Trunk road**: This is an important main road used by buses to travel long distances at a high speed.
U

- **Uniform delay**: this is the delay that is measured at an intersection while assuming uniform arrivals.
- **Un-signalized intersection**: an intersection which is not controlled by traffic signals
- **Upstream**: this is a term that refers to the direction from which traffic is flowing.

V

- **Velocity**: this is the rate of change of vehicle distance with time in a specified direction.
- **Vertical curve**: This is an important transition element in geometry design of highways that gives a transition between two sloped roadways and allowing vehicles to negotiate the elevation rate change at a gradual rate rather than a sharp cut.

W

- **Weight**: the force that gravitation exerts upon a body. An indication of how heavy a body is.

Y

- **Yellow interval**: the short interval just before a red in a traffic signal warning the driver that a phase change is about to occur.
- **Yield sign**: this is a sign that indicates to drivers that they must prepare to stop if necessary to let a driver on another approach proceed. Also called the give-away sign.
CHAPTER 1: INTRODUCTION

1.1 THEORETICAL BACKGROUND

Bus Rapid Transit (BRT) is a transit system that makes use of modern and state of the art buses to deliver quick, comfortable and relatively cheap services usually at metro-level capacity. A quick and high end service is achieved by including some features into the transit system. Such features include ‘bus-only’ lanes, designed and specially crafted stations, off-board fare collection and high arrival frequency of bus. [1].

The most ancient of the BRT system was the Rede Integrada de Transporte ('Integrated Transportation Network') deployed in a city called Curitiba, Brazil, and started operations in 1974 (source: Wikipedia). This has led to the development of this system around the world, South Africa inclusive.

However, there are certain set standards that a transit system must attain before it can be referred to as a BRT system. The most obvious is that buses must travel on a dedicated lane separated from the traffic for all (or almost all) part of the journey so that congestion on the other vehicular lanes does not affect the bus travel. Other features in which a standard BRT system incorporate include:

- Bus-only lanes designed to run at the center of the road. This is done to avoid curbside delays
- Bus Stations which have platform that has the same height as the floor of the bus. These reduce delay caused by climbing steps and also make the bus more wheel-chair accessible.
- Priority allocated to buses at signalized intersection.

Of utmost priority to this research is the last condition for a BRT; Bus priority at intersections.

One of BRT major benefits is travel time savings. BRT achieves travel time savings by using

- A dedicated bus-lane which is also a bus-only lane as shown in figure 1.1.
- A traffic signal priority system, which is done by advancing or extending the signal phase as shown in figure 1.2.

TCRP concluded that delays experienced at intersections because of control signals cause up to 20% of overall bus travel time and 50% or more of all other types of delay [2]. Therefore any effort geared at adjusting the signal timing to reduce delay and hence benefitting the BRT and the overall traffic flow will not only improve bus speed but also improve bus-reliability and the system’s capacity.
However, while trying to make adjustments to signal timing in order to favor BRTs, great care and caution must be exercised so as not to cause a greater damage to the overall traffic flow. ‘Signal controls for a BRT system can be achieved by using the passive, active, or real time priorities as well as pre-emption [4].

Passive priority techniques are usually employed where there was a pre-existing signal operation and cases where using additional facilities such as detectors are not feasible or are expensive. They are designed to minimize delays by modifying existing signal operation which might involve adjusting signal cycle length, if possible using a shorter cycle length, maximizing the green times along BRT corridors and minimizing the number of phases.

Active priority techniques make use of various techniques to detect the oncoming BRT bus and then adjust the signal timing by advancing or extending the artery green time to favor the oncoming vehicle within the established signal cycle as shown in figure 1.2. However, both extension and advancement of the green time cannot exist in the same signal cycle.

Real time priority technique has enjoyed the least application and requires specialized equipment as concluded by the TCRP. It put into consideration both bus and automobile arrivals at a single or network of intersections.

Preemption: this technique changes the normal signal phasing and sequencing to avoid delay of oncoming vehicle.

The reason for TSP is to reduce delay. Delay caused by traffic signals is called control delay. Delay is the most important MOE at a signalized intersection because it relates to the amount of lost
travel time, fuel consumption, and the frustration and discomfort of drivers [5]. It is one of the main factors on which level of service (LOS) rating is determined [6].

Several models have been developed to measure delays experienced at signalized intersections. Some of which are the highway capacity model, Akcelik delay model and Webster’s model.

Figure 1.2 Active Priority Concepts [7].

NOTE:
A. The minimum side street green is required in each cycle.
B. If the Artery green is advanced, it should not be extended in the same cycle, but
C. If the Artery green is extended, it should not be advanced in the next cycle.
D. Yellow intervals are not shown.
1.2 PROBLEM STATEMENT

This research focuses on the BRT system used in Johannesburg called the “Reavaya” (which means ‘We are going’) which is also the BRT system that was used as a case study. It is a common practice in other developed and developing countries that when a BRT system is built, it is important to include on its corridors a prioritized signal control at intersections that gives a right-of-way to the BRT. However, as noticed at traffic intersections, the Reavaya buses were not prioritized at intersections leading to extra control delay. This could be because the traffic signals were already in place at various intersections before the advent of the BRT in the year 2009. Therefore, as in most cases the bus traffic signals were only connected in phase with the existing signals. This practice has reduced the efficiency of the system by prolonging control delay experienced by the buses.

1.3 MOTIVATION OF RESEARCH

It is estimated that a prioritized traffic signal will reduce control delay of buses by 10% - 25% of the total bus travel times [8]. This has made prioritization of buses at intersections a more common practice. Also, in a research carried out by Furth et al [9], it was concluded that prioritized signal control could save the bus approximately 50 seconds of travel time but for the general traffic however, there were no delay savings recorded. By using the appropriate TSP system, control delay can be minimized for the buses with very little or no effect on the general traffic.

1.4 AIM OF THE RESEARCH

The aim of this research work is to measure the average control delay experienced by the buses at an un-prioritized signalized intersections and also to evaluate the impact of active prioritization on the transit of the buses and the flow of general traffic along the bus corridor.

1.5 OBJECTIVES OF THE RESEARCH.

The objectives of this research work are hereby highlighted:

1. To develop a model that measures the control delay experienced by a bus at an un-prioritized signalized intersection along the bus-only route.

2. To measure the control time delay experienced by the BRT buses at signalized intersections at off-peak periods.
3. To measure the control time delay experienced by the BRT buses at peak periods.

4. To analyze the effect of intersection geometry and complexity on delay of BRT buses.

5. To measure the effect of active signal prioritization on the transit of the buses.

6. To measure the effect of active signal prioritization on the flow of general traffic along the bus corridor.

1.6 HYPOTHESIS

The average control delay experienced by the bus at a signalized intersection was measured as well as the total travel time of the bus. It was expected that active prioritization of signals at signalized intersections will reduce the waiting time of buses at intersections. It was also expected that the active prioritization of signals will have little impact on the flow of general traffic along the bus corridor.

1.7 METHODOLOGY

To achieve the aim and objectives of this research, the following steps were taken:

1. A delay model that measures the bus delay along bus only route was proposed.

2. The delay model was compared with other models and field measurements technique for accuracy and afterwards was used to measure delay along bus only route at signalized intersections.

3. About 10 intersections which are on the BRT buses trunk corridor were identified on which the delay models were used.

4. The intersections chosen were of different types and complexity. This was done so that the various traffic conditions would be properly captured.

5. Selected morning peak period was 6am to 9am and selected evening peak period was from 4pm to 7pm.
To arrive at the effect of bus-only lane prioritization on the overall traffic of the intersection, SUMO; a traffic signal timing optimization and traffic simulation software was used.

1.8 DELIMITATIONS

- To measure the control delay, only the intersections along the route of the BRT trunk were considered.
- The delay model developed is suitable for bus only routes and to be used when headway of buses is adhered to.

1.9 SIGNIFICANCE OF THE RESEARCH

This study unveils the importance of a transit signal priority system to a BRT system by giving useful data as touching delay and travel times that pertains to the Reavaya and hence, more detailed. The study also proposed a delay model that incorporates the extra delay caused by bus deceleration and acceleration as a result of the control signal. A study was carried out on the effect of active prioritization (at signalized intersections) on the operation of the buses and the general traffic. A comparison was drawn between the effects of prioritized intersections and un-prioritized intersections. Knowledge from this research can also be used by cities or countries to build or improve their BRT system.

1.10 ORGANIZATION OF DISSERTATION

The rest of this dissertation is organized as follows: Chapter two presents a systematic review of un-signalized and signalized intersections and also discussed models that have been used to measure delay. Also, review of published literatures on types of intersection were presented in this chapter. Chapter three describes the methodology, procedures and field work that were employed in carrying out this research. Chapter four describes all the results, data generated from the field work, analytical models used and simulations carried out. Chapter five presents the conclusions arrived at from the research and a recommendation was also presented.
CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

Over the last few decades since the emergence of the first BRT service at Curitiba, Brazil in the year 1974, there has been a surge in the construction of the system around the world from the developing countries to the developed and advanced countries [10] [11] [12]. At different locations (states, countries, provinces, cities, etc.) the BRT system has been modified to suit the prevailing conditions of such location and the market it serves [13] [14] [15]. However, at the core of every implementation is the desire to offer a quick, easy, reliable and a cheap mode of transit for its market [16] [17] [18] [19] [20].

In this chapter, literature related to this subject of research is presented. The review is set as follows:

- Un-signalized intersection challenges
- Benefits of Signalized Intersection
- Signalized Intersection Delay Models
- Stopping sight Distance (SSD)
- Types of intersections and complexity
- Transit signal priority systems
- Simulation of road traffic using SUMO

2.2 UN-SIGNALIZED INTERSECTION CHALLENGES

This section explains un-signalized intersections and the challenges that come with them and therefore, the need for signals at intersections along bus only lane. Un-signalized intersections are flow facilities which are interrupted using controlled and uncontrolled access points that may also slow to a great degree the flow of traffic. These access points are basically stop signs, yield signs and other types of control but not traffic signals.

Un-signalized intersections are the more common type of intersections when compared with signalized intersections. Even though they contribute to the overall performance of traffic in an intersection, their capacities are lower than the signalized intersections. According to Troutbeck and Brilon, “In an Un-signalized intersections drivers are not guarded by physical and obvious indicators” [21]. The driver is not guarded but his left to make his decision of when it is the best
time to join an intersection. Usually, the driver seeks for a maneuvering chance (usually called “gap”) in the traffic to enter or exit an intersection as the case may be. This technique is often called gap acceptance. Gaps are equal to headways both are measured in seconds. At an un-signalized intersections, it is expected that drivers pre-empt the behavior of other road users and make a judgement based on his pre-emption giving priorities to other road users when necessary. If there are other vehicles that obviously have priority over the driver trying to join the traffic flow; depending on the nature of the intersection, the driver must yield to these drivers.

The gap acceptance theory is a theory used to explain the behavior of un-signalized intersections and it is a structured methodology of defining how much a driver can make use of a gap of known duration and size. An example is the question of if a driver can exit the stop line of a minor road given that time between successive vehicles on the major road is 10 seconds also, how many drivers can actually make a successful maneuver in this 10 second interval? Usually the smallest gap that drivers on the minor traffic flow are willing to accept assuming similar situation and circumstances is referred to as the critical gap. Troutbeck and Brilon pointed out that using the widely accepted drivers’ behavior model, drivers enter the intersection only when the gap between successive vehicles on the major flow is equal to the critical gap (or more than the critical gap) [22]. As an instance, if the critical gap was 5 seconds, then a 5 second gap between successive vehicles on a major stream is needed for a driver to enter the major stream. The driver will also require the same 5 seconds at all other times the same intersection is approached and the same is expected for every other driver that uses the intersection.

Another common assumption is quite a lot of drivers should have enough time to gain entrance into the intersection from a minor road in cases where we have gaps that are long. More often, vehicles which are expected to yield right of way because they are on the minor stream do enter the intercession in the long gaps at headways which is called the "follow-up time".

In the theory adopted in most manual for un-signalized intersections, there are two important assumptions made, they are that drivers are consistent in their decisions and that the drivers are homogenous. A driver is assumed to have the same reaction at every similar situations and time. The driver is not expected to refuse a gap and afterwards acknowledge a gap which is smaller. Since a homogenous situation is assumed, all drivers are expected to behave in just the same way given a circumstance. In reality, these conditions are unreasonable and difficult to attain as also argued out by Troutbeck and Brilon “To assume that drivers will be consistent and act the same for all types of approaches is not attainable and realistic” [21]. Catchpole and Plank, Troutbeck, and Wegmann all concluded that if drivers were assumed to be heterogeneous and not
homogenous, the entry capacity of the intersection would be greatly decreased but if drivers were assumed to be consistent and homogeneous instead of the more attainable inconsistent and heterogeneous assumption, then the difference in the result of the predictions will only be few percent [21] [22] [23] [24] [25]. Which can be interpreted that the cumulative effect of assuming that drivers will act the same and consistently is little and, to ensure simplicity, it is safe to assume a consistent and homogeneous driver behavior.

Research proved that the gap acceptance parameters (i.e. the critical time and the follow up time) may be affected by two factors they are:

- The speed of the major stream traffic [26] [23].
- The difficulty of the maneuver. The critical gap and other follow-up time parameters become longer as maneuver becomes more difficult.

According to Troutbeck and Brilon, there has also been a suggestion that drivers require a different critical gap when crossing different streams within the one maneuver [21]. For instance a turn movement across a number of different streams may require a driver having a different critical gap or time period between vehicles in each stream [27]. This is seen as an unnecessary complication given the other variables to be considered.

The complexity and unrealistic assumptions involved in un-signalized intersections makes it a complicated and relatively (when compared with the signalized control mechanism) unsafe intersection control mechanism.

2.3 SOME BENEFITS OF SIGNALIZED INTERSECTIONS

Traffic signals are traffic control mechanism which are electrically operated that give indication to pedestrians, cyclists and drivers allowing them to advance or impede their travels by assigning ROW to each approach and movement at different period. Traffic signals allow the use of flow facilities to be shared among road users by separating conflicting movements in time and allocating delay, which results into improved mobility and safety along the facility.

The use of traffic signals to achieve control at intersections has the following benefits:
- Optimization of travel time delay
- Reduction of crash frequency and/or severity
- Prioritization of specific roadway user type or movement (such as pedestrians or left turn movements)
• Accommodation of a new intersection approach or increase in traffic volumes (such as the addition of an approach at a new development)

According to the reports by FHWA, traffic signals are portrayed to play an important role in achieving safer traffic performance at intersections [28]. Research has also shown that the proper installation and operation of traffic signals can reduce the severity of crashes.

2.4 DELAY MODELS FOR SIGNALIZED INTERSECTIONS.

Delay is a very effective measure of effectiveness (MOE) at a signalized intersection since it involves the amount of lost time during travel, fuel consumption, and also include frustration and discomfort a driver might face [29]. It is one of the main factors on which level of service rating is determined [17].

Most delay models however do not estimate the delay caused by decelerating to stop and the delay caused by bus accelerating from stop to its normal travel speed because of the difficulties involved. The delay models measure basically the stopped time delay.

Delays are usually measured using three broad methods one of which is the direct measurement of traffic conditions on the field. Others are the use of simulation and the use of analytical models. Akgungor, A.P. and Bullen, A.G.R. argued that of these methods, the most convenient and pragmatic is the analytical estimation [29]. In order to estimate delay at signalized intersections, several analytical models using unique assumptions for various traffic conditions have been proposed and developed. Basic assumptions which were used by different stochastic steady-state delay models was that vehicles arrive randomly and have a uniform departure headways but these assumptions are not attainable and realistic. Stochastic steady-state delay models are best use for traffic conditions which are not saturated since it results to infinite delay as the capacity of the intersection is being approached. Deterministic models are the preferred and more widely used in predicting delay at intersections with over saturation but these models ignore the effect of randomness in traffic flow. Time dependent delay models have been developed to overcome the deficiencies in stochastic steady state and deterministic delay models having combining both using the co-ordinate transformation technique which makes the model (time dependent model) to be more realistic. There are three different time dependent delay models commonly used to estimate delay at signalized intersections. They are Australian, Canadian and the Highway Capacity Manual (H.C.M.). Though the above named models are the most commonly used, they find their source
Other delay models often used are the TRANSYT 8 and an alternative to the HCM (a slight variation of the HCM).

### 2.4.1 WEBSTER’S DELAY MODEL

1. **Uniform Delay Model:**

Webster’s delay model proposed in 1958 has been the bedrock of most delay models used. He proposed a uniform delay model using two basic assumptions. The assumptions stated that there is a stable flow of traffic and also that vehicles arrive in a uniform, patterned order. Figure 2.1 shows the arrival and the departure curves and the area between both curves can be assumed to be the aggregate delay experienced at the intersection. Webster Uniform delay model measures the area of the triangle formed by the curves which is half the base (R as seen in the graph) multiplied by the height (V). Therefore, the aggregate uniform delay (AD) can be written as:

\[
AD = \frac{RV}{2}
\]  

(1)

Where \(G\) is the duration of the Green phase, \(R\) is the length of the Red phase, \(V\) is the number of arrivals during the time \(R + t_c\). Length of red phase is given as the proportion of the cycle length \(C\) which is not green or:

\[
R = C \left(1 - \frac{g}{C}\right)
\]  

(2)
By setting number of arrivals during time \((R + t_c)\) to be the number of departures during time \(t_c\) we can have the length \(V\)

\[
V = v(R + t_c) = s t_c
\]  

(3)

Putting equation 2 into equation 3 and then making \(V\) the subject of the equation gives,

\[
v(C(1 - \frac{g}{C}) + t_c) = s t_c
\]

\[
t_c(s - v) = vC(1 - \frac{g}{C})
\]

\[
\frac{V}{s} (s - v) = vC(1 - \frac{g}{C})
\]

\[
V = C(1 - \frac{g}{C})(\frac{vs}{s} - v)
\]  

(4)

Putting equation 2 and 4 into 1 generates;

\[
AD = \frac{RV}{2}
\]

\[
AD = \frac{1}{2} \left[ C\left(1 - \frac{g}{C}\right)\right]^2 \left(\frac{vs}{s} - v\right)
\]

Where \(AD\) is the aggregate delay, in vehicle seconds. To obtain the average delay per vehicle, the aggregate delay is divided by the number of vehicles processed during the cycle, which will be arrival rate, \(v\), multiplied by the full cycle length, \(C\). So we have,

\[
UD = \frac{1}{2} \left[ C\left(1 - \frac{g}{C}\right)\right]^2 \left(\frac{vs}{s} - v\right) \left(\frac{1}{vC}\right)
\]

\[
UD = \frac{1}{2} \left( \frac{C(1 - \frac{g}{C})^2}{1 - \frac{v}{s}} \right)
\]  

(5)

Another way of writing the equation is to use the capacity \(c\), instead of the saturation flow rate, \(s\). Given that

\[
s = \frac{c}{(g/c)}
\]  

(6)

So, uniform delay becomes,

\[
UD = \frac{1}{2} \left( \frac{C(1 - \frac{g}{C})^2}{1 - \frac{gv}{Cc}} \right)
\]
where, UD is the uniform delay (sec/vehicle) C is the cycle length (sec), c is the capacity, v is the vehicle arrival rate, s is the saturation flow rate or departing rate of vehicles, X is the v/c ratio or degree of saturation (ratio of the demand flow rate to saturation flow rate), and g/C is the effective green ratio for the approach.

2. Random Overflow Delay:
A major assumption in the Webster’s uniform delay is that the arrivals is always much less than the capacity of intersection and hence there is no overflow of vehicles at the end of each cycle during the analysis period another assumption was that the arrival rate was uniform but at isolated intersections, vehicle arrivals are more likely to be random. This model assumes that arrivals are Poisson distributed, with an underlying average rate of v vehicles per unit time and also considers random arrivals and the fact that some individual cycles within a demand period with v/c < 1.0 could fail due to its randomness. The additional delay caused is referred to as Random delay.

\[
RD = \frac{X^2}{2v(1-X)}
\]

Where, RD is the average random delay per vehicle, s/veh, and X is the degree of saturation (v/c ratio). Webster found that the above delay formula overestimate delay and hence he proposed that total delay is the sum of uniform delay and random delay multiplied by a constant for agreement with field observed values.

The Total Delay is given as:
\[
D = 0.90(UD + RD)
\]

3. Continuous Overflow Delay:
Over saturation is said to occur when the arrival vehicles are more than the capacity of the intersection. However this could occur during one or two cycles during observation or the situation may extend over a long period of time. If it occurs over an extended period of time and queues grow continuously the overflow is said to be continuous. Therefore, to account for this, an overflow delay is added to the uniform delay as shown in fig 2.2. Figure2.2 is a situation where v/c > 1.0
The highest value of $X$ is 1.0 for uniform delay, so Uniform delay can be simplified as,

$$UD = \frac{1}{2} \left( \frac{C(1 - \frac{g}{C})^2}{1 - X \frac{g}{C}} \right)$$

$$UD = \frac{1}{2} C \left( 1 - \frac{g}{C} \right) \quad (10)$$

The Total Continuous Overflow Delay can be estimated from figure 2.7 as,

$$TOD = \frac{1}{2} T(vT - cT) = \frac{T^2}{2} (v - c) \quad (11)$$

**Figure 2.2:** Illustration of Continuous overflow delay model [31]

**Figure 2.3:** Derivation of the overflow delay model [31]
Where, TOD is the total or aggregate overflow delay (in veh-secs) and T is the analysis period in seconds. Average delay is obtained by dividing the aggregate delay by the number of vehicles discharged within the time T which is cT.

\[
OD = \frac{T}{2} \left( \frac{v}{c} - 1 \right) \tag{12}
\]

The above delay comprises only the delay experienced by vehicles through time T, it does not include additional delay experienced by vehicles in the queue after time T. The above quoted delay equation is time dependent i.e., the longer the period of over-saturation, the larger delay becomes. If a time period of T1 to T2 was observed, a model for average overflow delay during this time period is shown in equation 13 and as illustrated in Figure 2.3 and 2.4, the delay area formed is a trapezoid, not a triangle.

\[
OD = \frac{T_1 + T_2}{2} \left( \frac{v}{c} - 1 \right) \tag{13}
\]

Equation 13 is used to estimate the average delay per vehicle that is experienced during the specified interval, T1 through T2. Therefore, delays experienced by vehicles that arrived before time T1 but departed after T1 are included only to the extent of the delay recorded within the specified times (i.e. T1 and T2) and delay that might have been experienced as a result of the queue

![Figure 2.4: Overflow delay between time T1 & T2](image)
before T1 was discarded. Similarly, the model does not accommodate vehicles delay experienced after time T2.

### 2.4.2 OTHER DELAY MODELS

According to equation 8 and 12, Webster’s Random delay is given as:

\[
RD = \frac{X^2}{2v(1 - X)}
\]

And continuous overflow delay given as,

\[
OD = \frac{T}{2(X - 1)} \quad \text{since } X = \frac{v}{c}
\]

As shown in figure 2.5, there appear to be some inaccuracy when the X approaches 1.0. When X < 1.0 Webster’s random delay model can be applied because the Webster's random delay has the 1-X term at the denominator, therefore, as X approaches 1.0 random delay becomes infinite. In a case of X>1.0 overflow delay model may be applied. Overflow delay has (1 – X) term as the numerator, so as X approaches to 1.0 overflow assumes a value of zero but has a uniform increase as the value of X also increases. The two models are inaccurate as X approaches (or is equal to) 1.0 since Delay should not have an infinite value when X becomes 1. So the model does not measure the true overflow when X is 1.

![Figure 2.5: Comparison of overflow & random delay model [31]](image-url)
This inaccuracy of Webster’s model as $X$ approaches 1 has brought about the development of other delay models. In the year 1981, the Australian model was developed [32], 1984 the Canadian Model [33], 1985 the Highway capacity model [34] and 1988 Akcelic model [35]. The above listed models were developed from the Webster’s model and have similar terms with distinguishing assumptions. The generalized two term equation of these models is given below:

$$d = \frac{0.5C (1 - U)^2}{1 - UX} + 900T x^n \left[ (x - 1) + \sqrt{(x - 1)^2 + \frac{m x - x_0}{QT}} \right]$$  \hspace{1cm} (16)$$

Where:

$d$ = average overall delay (including stop-start delays) in seconds/veh.

$U = g/C$ (ratio of effective green time to the cycle time)

$C$ = signal cycle time in seconds

$x$ = degree of saturation (ratio of arrival flow rate to capacity)

$T$ = flow period measured in hours

$Q$ = capacity of intersection in vehicles per hour

$m$, $n$ = calibration parameters

$x_0$ = the degree of saturation below which the second term of the delay formula is zero.

$x_0 = a + bsg$

Where:

$sg$ = capacity per cycle ($s$ = saturation flow rate in vehicles per second and $g$ = effective green time measured in seconds)

$a$, $b$ = calibration parameters.

The first term of equation 16 measures the Uniform delay and the second term measures delay as a result of an overflow. Australian, Canadian, the Highway Capacity Manual, Akcelic and the TRANSYT 8 models can be obtained by setting parameters $a,b,m,n$ to the appropriate value [35].

A close look at equation 16 reveals that only the second term of the equation changes for the three models since only the second term has the calibration parameters. Table 2.1 shows the different values of the calibration parameters for the Australian, Canadian, the HCM, Akcelic and the TRANSYT 8 model.
Table 2.1: Calibration Parameters Value for the Australian, Canadian, HCM, Akcelic and TRANSYT 8 Delay Model (to be substituted into equation 16) [35].

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>m</th>
<th>a</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australian</td>
<td>0</td>
<td>12</td>
<td>0.67</td>
<td>1/600</td>
</tr>
<tr>
<td>Canadian</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>HCM</td>
<td>2</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Akcelic</td>
<td>0</td>
<td>8</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>TRANSYT 8</td>
<td>-1</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

2.5 STOPPING SIGHT DISTANCE.

Any delay experienced at an intersection (signalized or un-signalized) starts when the driver sights the intersection or the traffic signals after which he makes his decision of decelerating or stopping. Stopping sight distance is the minimum distance without view obstruction of any kind or the worst case distance in road design that must be provided for a driver in order to allow him to stop before collision with road way obstruction, stopped vehicles, road debris and pedestrians.

Stopping sight distance comprises of two terms which are:
- The distance travelled during perception reaction time ($D_{pr}$)
- The distance travelled during decelaration, stopping of the vehicle ($D_{b}$).

The perception reaction time is the time required for a driver to recognize, interpret and decide what reaction to be taken as a result of a road condition or situation. The sum of the distance travelled during perception-reaction time and the distance travelled during deceleration, stopping of the vehicle is the Stopping sight distance as shown in equation 17.

\[
\text{Stop Sight Distance (SSD)} = D_{pr} + D_{b} \quad (17)
\]

The American Association of State highway and Transportation Officials (AASHTO) estimates a second for reaction time and 1.5 seconds for perception time making a total of 2.5 seconds for the perception – reaction time. This is a worst case scenario and the value may vary slightly from one location to the other.

The Driver Perception- Reaction distance can be written as:

\[
D_{pr} = Vt \left(\frac{1000}{3600}\right) = 0.27778Vt \quad (18)
\]
Where:

\( D_{pr} \) = distance travelled during perception reaction time

\( V \) = design speed of the road facility (km/h)

\( t \) = brake reaction time (seconds).

The Braking distance \( D_b \) can be calculated as:

Kinetic Energy of bus = Work done to stop bus

\[
\frac{1}{2} m v^2 = D_b \times \text{frictional force}
\]

\[
\frac{1}{2} m v^2 = D_b \times \mu R
\]

\[
m v^2 = 2 D_b \times \mu m g
\]

\[
D_b = \frac{0.0386 v^2}{\mu g} \tag{19}
\]

Where:

\( D_b \) = Braking distance

\( V \) = design speed of the road facility (km/h)

\( \mu \) = coefficient of friction between the vehicle tires and the surface of pavement

\( g \) = acceleration due to gravity.

\( R \) = normal force on the vehicle

\( m \) = mass of vehicle.

The Stopping sight distance can therefore be written as:

\[
\text{SSD} = D_{pr} + D_b
\]

\[
= 0.27778 V t + \frac{0.0386 v^2}{\mu g} \tag{20}
\]

AASHTO design values for coefficient of static friction for highways and arterials based on the result of some field works on wet pavements is given in table 2.2

Table 2.2 AASHTO Recommendations for Coefficient of static friction (\( \mu \)) [36].

<table>
<thead>
<tr>
<th>Speed (km/h)</th>
<th>&lt;30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>&gt;80</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu )</td>
<td>0.40</td>
<td>0.38</td>
<td>0.37</td>
<td>0.36</td>
<td>0.35</td>
</tr>
</tbody>
</table>
2.5.1 STOP SIGHT DISTANCE AND HORIZONTAL CURVES.

Horizontal curve on highways and arterials is a result of pavement moving along hills, giant obstacles that are immovable, rivers and mountains as shown in figure 2.6. Horizontal curve limits the available sight distance for the drivers. Hence, horizontal curves are usually designed with the minimum stopping sight distance for the road facility in mind. The desired stopping sight distance for a horizontal curve is obtained using equation 20.

It therefore becomes important to estimate the value of the horizontal sight line offset (M) that will allow for the desired stopping sight distance as shown in figure 2.7. A stop sight distance (SSD) sight line obstruction is any object (hills, mountains, trees, buildings, etc) located inside the horizontal sight line offset distance and is at least two feet above the road way surface at the center line of the lane on the inside of the curve. Equation 21-25 shows how the value of the horizontal sight line offset (M) can be obtained.
If the arc of the horizontal curve is longer than the stop sight distance then,

\[
SSD = \frac{\pi}{180} R \cdot \alpha_{SSD} \tag{21}
\]

But \( M = R \left(1 - \cos \frac{\alpha}{2}\right) \tag{22}\)

Substituting for \( \alpha \) in (22) from (21)

\[
M = R \left(1 - \cos \left[28.65 \cdot \frac{SSD}{R}\right]\right) \tag{23}
\]

Making SSD subject of equation (23) gives equation (24)

\[
SSD = \frac{R}{28.65} \left(\cos^{-1} \left[\frac{R - M}{R}\right]\right) \tag{24}
\]

Where:

\( \alpha_{SSD} \) = central angle for an arc equal to the desired SSD

SSD = Stop Sight Distance

M= Horizontal sightline offset measured from the centerline of the inside lane of the curve to the sightline obstruction in ft

\( R \) = radius of the curve in ft.

If the stop sight distance is longer than the arc of the horizontal curve then,

\[
M = R \left(1 - \cos \frac{28.65L}{R}\right) + \left(\frac{SSD - L}{2}\right) \sin \frac{28.65L}{R} \tag{25}
\]

Where \( L \) = length of arc of horizontal curve.

2.6 TYPES OF INTERSECTIONS AND COMPLEXITY

An intersection is an area being shared among two or more roads. At this area, vehicles are provided with change of route directions. There are generally two types of intersections, they are

- Grade Separated intersection which are also known as interchanges
- At Grade Intersections.
2.6.1 GRADE SEPARATED INTERSECTION OR INTERCHANGE.

This can simply be said to be a junction of highways which are on different levels (or grade) that facilitates the crossing of one traffic to the other without crossing the traffic streams. It is designed such that there is no grade crossing conflict while allowing other maneuvers by converging, diverging and weaving at a designed speed. The interchange can be directional (i.e. ramps follow the direction of the flow of traffic) or non-directional (there is a change in the direction of traffic flow). The following are different forms of interchange:

- Over pass: it is a common form of interchange also called the “flyover”. It is a road, railway or bridge that crosses over a highway, intersection or a railway. If it was designated to allow pedestrians to cross over major highways safely then it is called a Pedestrian overpass. Figure 2.8 shows an overpass interchange.

![Figure 2.8 An Overpass interchange](image)

- Underpass: An underpass interchange is a road, path or a passage way that runs under another road or a railway and is usually designed to have an entrance and an exit. Figure 2.9 shows an underpass.
• Diamond interchange: Usually used when a free way would be made to cross over a minor road as shown in figure 2.10

Figure 2.10 Diamond interchange [41]

• Trumpet Interchange: This is designed such that at least one loop ramp connect to the traffic either by leaving or entering the terminating expressway with the far lanes of the continuous highway. Figure 2.11 shows a trumpet interchange.
Cloverleaf Interchange: it is called so because it resembles a four leaf clover by design. It allows ease of traffic movement between two intersecting highways. It does this by allowing one of the highway to run over the other and both joined by a system of curved feeder roads which allows vehicles to leave and enter the highway as shown in figure 2.12.
• Partial Cloverleaf interchange: it is a variant of the cloverleaf interchange. It has fewer loop ramps. figure 2.13 shows a partial cloverleaf interchange

![Partial cloverleaf interchange](image)

Figure 2.13 Partial cloverleaf interchange [44]

• Directional Interchange: They are interchange that are designed to give direct connections to major turning movements as shown in figure 2.14.

![Directional interchange](image)

Figure 2.14 Directional interchange [45]

### 2.6.2 AT-GRADE INTERSECTIONS.

These are areas where two or more road meets whereby all change of route direction occurs on the same grade or plane. All intersections along the Reavaya route are at-grade intersections. It can be a roundabout at grade intersection or the standard at grade intersections.

• Roundabout Intersection: A roundabout intersection is an intersection where drivers travel round a circle anticlockwise around a center island. Most modern designs do not
have stop or traffic signals making it cheap to implement and yet efficient. Figure 2.15 shows a roundabout intersection.

![Roundabout Intersection](image)

Figure 2.15 Roundabout intersection [46]

- **Standard At-grade Intersection**: They come in different designs all geared towards improving the level of service of the intersection.
  - Flared Intersection: They are special designs usually used to separate turning movements from the through movements. They are used at intersections with very high volume. Figure 2.16 shows a flared intersection.
  
  ![Flared Intersection](image)
  
  Figure 2.16 A Flared intersection [46]

  - Channelized intersection: This is an intersection that makes use of raised islands or markings to direct pedestrians or vehicles to follow a particular route or path as shown in figure 2.17.
Simple Intersections: In a simple intersection the minor and the major lanes maintain the streets cross section with no auxiliary turning lanes. Figure 2.18 shows a simple intersection.

2.6.3 COMPLEXITY OF INTERSECTIONS

The Reavaya bus-lane cuts across different types of intersection but most of which are those with four approaches. Intersections have a minimum of two approaches but it can have up to six or more approaches. The most common complexity is that with three or four approaches.

- Intersections with three: It can be in the “T”, skewed T and “Y” design. Figure 2.19 shows three approaches intersection in it different design forms
Intersections with four approaches: The right angle intersection, oblique intersection and offset intersection. Figure 2.20 shows intersections with four approaches.

Multi approaches Intersections: These are intersections with five or more approaches as shown in figure 21.

2.7 EFFECTS OF INTERSECTION COMPLEXITY AND GEOMETRY ON DELAY AT INTERSECTIONS.

In the previous section, the different types of intersections have been discussed. This section focuses on the effects that the geometry and complexities of these intersections have on the delay
experienced at such intersections. The geometry and complexities under focus include number of intersection legs, skewed or un-skewed, presence of vertical or horizontal curves.

2.7.1 EFFECT OF NUMBER OF INTERSECTION LEGS ON DELAY

The number of intersection legs has an obvious effect on the length of delay experienced at such intersections. As the number of intersection legs increases the conflict points at intersection increases. The number of conflict points at a three-leg intersection is 9; 3 of which are crossing conflicts, 3 are merging conflicts and 3 are diverging conflicts as shown in figure 2.22. For a four-leg intersection the number of conflict points is 32 for a 5-leg intersection the number of conflicts is 80 and for a six-leg intersection the number of conflicts is 168. However, the number of conflicts at a roundabout intersection is 8 [52].

It is therefore expected that the more legs an intersection has the more the delay that would be experienced at such intersection since both the intersection area and available time would be shared by more conflicting movements.

![figure 2.22 Conflicting movements in three and four legs intersections [53]](image)

2.7.2 EFFECT OF SKEW AT INTERSECTIONS.

The performance of an intersection is not just influenced by the number of legs at the intersection but much more also by the configuration of the intersection legs. As pointed out by Othman C.P et al. the configuration of the intersection legs can create difficulties in turning movement of vehicles, longer crossing time for pedestrians and reduction in the driver’s sight distance [54]. Othman also argued that a skewed intersection (an intersection where the intersecting highways are not precisely perpendicular) may cause the drivers to have reduced reaction time at the intersection while also
increasing the clearance time of vehicles at the intersection. He also argued that turnings experience longer distance along the curved path when merging with the major traffic.

Othman carried out a study where he evaluated the effect of skewed angles (which are more than 30 degrees) on the control delay of the minor approach. In his research, he observed traffic parameters at signalized intersections, modelled his observations as seen on the field and then modelled the same intersections with skews so as to unveil the effect of skews. From his result, it was shown that skewing a minor approach to the right caused a delay that was about 8.31% higher than the values obtained when the minor approach was perpendicular[54].

Safety issues were raised by Hanna, J.T. et al. when he concluded that the presence of skew angle in a Y- intersection makes it to have a 50% higher accident occurrence when compared with an un-skewed T- junction [55].

In a study by Garcia A., where he evaluated the impact of lateral visibility on safety of traffic movement at skewed intersection, it was concluded that for safety of movements to be maintained at a skewed intersection, the crossing maneuver angle must be 70 degrees or more and the merging movement angle must be 7 degrees or more [56].

Garber N.J. et al. explained that skewing an intersection produces an increase in distance of the intersection area which means a vehicle will have to travel more distance before exiting the intersection. He further pointed out that the extra distance travelled by vehicles must be factored in to the signal timing of that intersection so as to allow for good clearance of the vehicles [57].

Neuman, Gattis and Walker also argued that a skewed intersection has a larger intersection area which would make vehicles to be exposed to conflicting traffic for a longer time (in a case where the intersection is not actively controlled) [58-60] as shown in figure 2.23. They also argued that at skewed intersections, it is possible that sight distances are greatly reduced in some directions as a result of the driver’s strain in turning his head so as to have a good view of the conflicting approach. Therefore, a driver with the intention of making right turn might encroach into the oncoming lane in his attempt to have a good view of the conflicting approach because the intersection was right-skewed [58][59]. This phenomena is more frequent with older drivers.
2.7.3 EFFECT OF HORIZONTAL AND VERTICAL CURVES ON DELAY AT INTERSECTIONS.

The line of a stretch of road is made up of straight lines joined together by curves which helps to change the road alignment, the road direction and slope. Typically, curves that help to change and manipulate the alignment and direction of roads are called horizontal curves while curves that help to change slope of roads are called vertical curves.

Delay at intersections with curves are usually expressed as reduction in speed as vehicles approach the curves. For horizontal curves, the radius of the curve has a direct relationship with the safe velocity with which a vehicle can travel along it as seen in equation 26. Hence, the larger the radius of curvature, the more the speed with which a driver can travel and the less the delay that would be experienced at such intersections [61]. This is truer for an un-signalized intersection than a signalized intersection.

\[ R = \frac{V^2}{15(e \pm f)} \]  

(26)

Where:

\( R \) = radius of horizontal curve (ft)

\( V \) = design speed (mph)

\( e \) = super elevation

\( f \) = side friction factor.

In signalized intersection where the signals are needed to be sighted for good intersection control, drivers are compelled to slow down because travelling with a higher velocity than the designed...
velocity for the curve would shorten the stop sight distance available for the driver as seen from equation 20.

Vertical curves with longer curve length present a longer sight distance to drivers. A longer sight distance reduces delay at intersection since drivers can make judgement quicker. Hence, the longer a curve length the less the delay that could be experienced at the intersection

2.8 TRANSIT SIGNAL PRIORITY SYSTEM

TSP is a term that refers to a set of operational improvements that uses technology to reduce control delay at traffic signals for transit vehicles either by holding green lights longer or shortening red lights as seen in figure 2.24. Figure 2.24 is a schematic flow of traffic signal priority used in the city of Portland, United States. As reported by the World Bank, signal priority is usually used to complements other priority measures in the running way such as dedicated lanes, reserved ways, and priority pull outs etc. [62].

![Diagram of TSP](image)

Figure2.24 a schematic flow of TSP used in Portland. [63]
In their report, Harriet R. Smith et al described TSP as a system which is implemented with the aim of making transit service to be more cost effective and faster in its operations as it increases in its reliability [64]. They also pointed out that TSP when well implemented has a negligible effect on the overall traffic performance and is a cheap method of making bus rapid transit more competitive with the automobiles. TSP system also helps in reducing the overall travel time of the bus as pointed out by Levinson that delays experienced by buses at traffic signals account for 10% to 20% of all bus travel times and accounts for over 50% of the total delay experienced by the bus [65].

2.8.1 BUS SIGNAL PRIORITY TREATMENTS

There are several types of traffic signal priority treatments which are:

- The passive priority treatment
- The active priority treatment
- Real time Priority treatment
- Preemption Priority treatment.

Table 2.3 shows these priority treatments and a brief description of how they operate.

Table 2.3 Bus signal Priority System [65]

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Passive Priority</strong></td>
<td></td>
</tr>
<tr>
<td>• Cycle length adjustment</td>
<td>Reduction of cycle length to benefit the bus. Best for isolated intersections</td>
</tr>
<tr>
<td>• Use of Split Phases</td>
<td>The initial cycle length retained but a special phase for the bus movement is introduced</td>
</tr>
<tr>
<td>• Area Wide Timing Plans</td>
<td>Signal offset is used to give preferential progression to the bus</td>
</tr>
<tr>
<td>• Bypass metered signals</td>
<td>The use of special signal phases and rerouting of buses to non-metered signals</td>
</tr>
<tr>
<td>• Adjust Phase length</td>
<td>Approaches used by the bus is given more green time</td>
</tr>
<tr>
<td><strong>Active Priority</strong></td>
<td></td>
</tr>
<tr>
<td>• Green Extension</td>
<td>Bus phase is given more green time</td>
</tr>
<tr>
<td>• Early Start (Red Truncation)</td>
<td>Green for buses is earlier by reducing other phase time</td>
</tr>
<tr>
<td>• Special Phase</td>
<td>A bus phase is incorporated into the traffic signal</td>
</tr>
<tr>
<td>• Phase Suppression</td>
<td>Some phases are skipped to give priority to the bus</td>
</tr>
<tr>
<td><strong>Real –Time Priority</strong></td>
<td></td>
</tr>
</tbody>
</table>
• Delay-Optimizing Control | Real time change in the timing of the signals to give bus priority.
• Network Control | The system takes into consideration the overall traffic performance and make changes to signal timings to reduce delay

| Preemption | The approach of a bus terminates the running phase and signal returns to the bus phase. |

2.8.2 TECHNIQUES OF TSP SYSTEMS

The sonic and the optical pulse are one of the several ways in which a bus can communicate with the traffic signals but more recently there has been the use of AVL system to communicate with traffic signals. Harriet R. Smith et al explained four sub systems of a TSP system which are [54];

• Detection system: This system detects and delivers the location of the vehicle, its time of arrival and other useful information to a device that is connected to a Priority Request Generator.
• A Priority Request Generator: as the name implies, the system request priority from the traffic control system.
• Priority Control Strategies: this uses a traffic control system software enhancement system which assigns a range that addresses the functional requirements of the traffic jurisdiction.
• TSP System Management: this includes the fusion of both traffic and TSP functions which involve transit management and traffic control management that can configure settings, log events and provide reporting capabilities.

O’Brien W. explained the widely accepted steps that are involved in assigning priority at signalized intersection [66]. They are as follows:

• At some distance X before the intersection, the bus is detected as seen in figure 2.25. Various detection systems that are used to carry out this function are discussed in the next section.
• A request is then passed on to the priority request generator unit informing it that a bus is approaching while notifying the traffic control system that the vehicle will like to be granted priority. The priority request is then processed and a decision would be taken whether to allow priority based on pre-defined conditions. The traffic controller C (in
figure 2.25) then initiates the action to provide priority based on the defined priority control strategies.

- The bus crosses the intersection and clearance is detected by the clearance detection system at Y (in figure 2.25) and this informs the traffic controller that the bus has cleared the intersection.

- After a notification which confirms that the bus has cleared the signalized intersection, the traffic controller marked as C restores the actual signal timing using an already pre-determined logic.

![Figure 2.25 a representation of Traffic signal prioritization process [67]](image)

2.8.3 VEHICLE DETECTION SYSTEM

Vehicle detection systems have developed in the last few decades with various technological improvement to aid ease of use and maintenance [68] [69] [70] [71]. The oldest vehicle detection system is the use of a transponder and a tag based system (as seen in figure 2.26) which allocates priority to all buses. In recent times, a much more advanced AVL or UTC systems is now being used which gives a real time bus management, passenger information at stations and a selective priority for buses at signalized intersections which improves bus frequency and reliability [72].
Advantages and Disadvantages of various detection technologies are explained in table 2.4.

2.8.4 ADVANTAGES OF TSP

Research carried out in the United States revealed some of the advantages of a TSP system. As reported by Harriet R. Smith et al. some researches revealed the following [72];

- In Tacoma, there has been a reduction in delay by almost 40% in two corridors when signal optimization and TSP were combined.
- TRIMET a bus, commuter and light rail transit service provider in Portland, Oregon did not need to add one more bus to their fleet by implementing a TSP system which resulted to a 10% advantage in the overall travel time and also gives a 19% reduction in travel time variability and this has helped the transit service provider to reduce its scheduled recovery time.
- A reduction time of about 3 minutes in travel time was achieved by Chicago Pace, a BRT system in Chicago. The BRT system was also able to gain an advantage of one week day bus even though the frequency of the buses were maintained.
- Los Angeles Orange line was able to realize 25% of bus travel times by implementing TSP.

Fig 2.26 Bus detection using Transponder and tag system [73]
Casey et al. and Goeddel in a research conducted by the Los Angeles County Metropolitan Transportation Authority and summarized by the Federal Transit Administration analyzed twenty four signal priority projects and the following were their results [74][75].

- At Atlanta, Georgia, the research was conducted on 25 buses along one bus way. The aim of the research was to find out what happens to the travel times by shortening the red time of the approach. It was found out that the average travel time inbound for the entire route improved from 41.8 minutes before adjusting the red times (it was shortened) to 28 minutes after the adjustment (resulting to a 33% decline). In the outbound direction, the time improved from 33.1 minutes before adjusting the red times to 27.5 minutes after the adjustment has been made (a 16.9% improvement).
- At Maryland (Anne Arundel County). The research was conducted on 12 buses and 14 intersections. It was reported that for a 52 minute trip, a total of 10 minutes were saved.
- At Tacoma, Washington. The research was conducted on a 3.1 miles Pierce Transit which included 11 intersections and 15 buses. The result showed that 6% average travel time reduction was achieved.
- At Ontario, Canada, Toronto Transit Commission studied 10 buses traveling over 210 intersections. It was reported that peak period travel time declined by 2 to 4%.
- At Los Angeles, metro rapid buses along Wilshire-Whittier Boulevards and Ventura Boulevard recorded a 25% decline in overall travel time of which signal priorities yielded a 30% savings which is a 7.5% travel time decline. The delay caused to the other lanes were negligible.

Table 2.4 Advantages and Limitations of Various Vehicle Detection Technologies. [76]

<table>
<thead>
<tr>
<th>Technology</th>
<th>Suppliers</th>
<th>Features</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF with Low Frequency</td>
<td>Vapor VECOM using LSTS</td>
<td>System make use of inductive radio technology with vehicles making use of transmitters and other standard loop detectors or pavement imbedded antennas; transmitter factory can also be programmed or interfaced from an onboard keypad.</td>
<td>Cheap transmitters which are easy to maintain</td>
<td>Accumulated snow or any foreign object on tag may disrupt the transmission of message</td>
</tr>
<tr>
<td>between 100-150 Khz.</td>
<td>MFS; Detector Systems/LOOPCOM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Use of Radio Frequency @</td>
<td>TOTE/AMTEC H; AT/COMM</td>
<td>System make use of transmitter tags installed on top or side of buses and antennas installed overhead or roadside; has been deployed for use in the collection of toll, rail car and containerized cargo Identification;</td>
<td>Cheap transmitters which are easy to maintain; can be used</td>
<td>Accumulated snow or any foreign object on tag may disrupt the transmission of message</td>
</tr>
<tr>
<td>900-1000 MHz.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Use of Spread Spectrum Radio.</td>
<td>Econcile/EMTRAC; Automatic Eagle Signal and Tracker System</td>
<td>Sweeps narrow band signal over broad part of frequency spectrum; uses transmitter with directional antenna and an electronic auto compass in each priority vehicle and receiver with Omni-directional antenna at each intersection.</td>
<td>Often used to transmit bulky information.</td>
<td>Not as accurate in locating buses as other radio frequency technologies; possibility of being influenced by bad weather conditions; It may be not as cheap as others.</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>----------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------</td>
<td>-----------------------------------------------</td>
<td>--------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Use of Infrared</td>
<td>Siemens/ HPW infrared</td>
<td>Signpost at road side picks and reads signals; the AVI technology is mostly used by the Europeans</td>
<td>Have been used and tested over a period of time.</td>
<td>Limited ability to provide precise vehicle information; limited amount ban be transmitted from vehicle; requires line of sight.</td>
</tr>
<tr>
<td>Video</td>
<td>Racal communications video with ALPR software</td>
<td>System uses video camera coupled with advanced License Plate Recognition Software</td>
<td>Needs a clear and unobstructed line of sight.</td>
<td></td>
</tr>
<tr>
<td>Optical</td>
<td>3M and Opticom</td>
<td>The system makes use of a light emitter that has been attached to a transit bus at a different frequency than emergency vehicles which usually would have a higher priority.</td>
<td>Offers a good advantage if intersections have been equipped with Opticom emergency preemption equipment.</td>
<td>May not be able to give an accurate information about the exact location of the; Needs a clear and unobstructed line of sight</td>
</tr>
<tr>
<td>Tracking of Vehicles</td>
<td>IBM/ Vista System; TDOA &amp; FDOA Tracking</td>
<td>The system operates by using time difference of arrival and frequency difference of arrival to locate and track radio frequency transmissions from the vehicle’s emitter.</td>
<td>May not be able to give an accurate information about the exact location of the; Needs a clear and unobstructed line of sight for signal priority treatment.</td>
<td></td>
</tr>
</tbody>
</table>

2.9 SIMULATION IN SUMO.

SUMO is an acronym for “Simulation of Urban Mobility” [77] [78]. SUMO is a microscopic road traffic simulation. As reported by Krajzewicz, the design of the software started in the year 2000 and was first implemented in the year 2001. The project started with a collaboration work between the Center for Applied Informatics Cologne and the Institute of transportation systems (at the German Aerospace Center) [79]. SUMO is an open-source software under the General Public |
License and it is available in the compiled executable form and as a source code. It can be used both on the Linux and the Windows platform [80].

The SUMO core models include the models that describe the vehicles’ longitudinal behavior which can also be referred to as the “car-following” model and the models that describe the vehicles’ lateral behavior also referred to as the “lane-changing” model. In SUMO the car-following models and the lane-changing models are computed separately. The car-following models are executed first and then the lane-changing models afterwards.

2.9.1 SUMO CAR-FOLLOWING MODELS

The car-following model used in SUMO is similar to the model formulated by Krauß in the year 1998 [81] but with some improvements. The model was anchored on deriving a safe gap in which the “follower” (a vehicle running behind another vehicle) would have to stop behind the “leader” (a vehicle ahead of another vehicle) without any collision. In this derivation, the follower’s and the leader’s maximum decelerations and the follower’s reaction time are used to compute the safe speed of the follower. The safe speed of the follower is given in equation 27

\[
V_{sv}(t) = -\sigma + \sqrt{(\sigma d)^2 + V_l(t-1)^2 + 2\sigma g_l(t-1)}
\]  

Where:

\[V_{sv}(t)\] = safe velocity at time t (m/s)

\[\sigma\] = follower reaction time (sec.)

\[d\] = maximum deceleration ability (m/s^2)

\[V_l(t)\] = leader’s velocity at time t (m/s)

\[g_l(t)\] = gap at time t (m). The gap is measured from follower’s front to leader’s back.

With the safe velocity of the follower known, the desired velocity of the follower would then be calculated using equation 28

\[
V_{dv}(t) = \min\{V_{sv}(t), v(t-1) + a, V_{max}\}
\]  

Where:

\[V_{dv}(t)\] = velocity which the follower desire to use (m/s)
\[ v(t) = \text{current velocity of follower (m/s)} \]

\[ a = \text{maximum acceleration ability of follower (m/s}^2) \]

\[ V_{\text{max}} = \text{maximum velocity of follower (m/s)}. \]

Brockfeld, Kühne and Wagner proved that the Krauß model is valid enough when compared with other models [82-84] and can be executed quickly because only few computations are needed.

Krajzewicz reported that when using this model for complex scenarios which involve road networks of random length, right of way rules which are complex, different vehicle routes and traffic lights, further adjustment and calibration are needed to make the model work. The following adjustment and computations were done:

- The velocity of the follower was made to depend on the leader’s speed and distance between them
- The speed allowed on the next lane was adapted.
- In a scenario where the follower has no right-of-way at the next intersection, then two velocities were calculated. The first calculated velocity was for crossing the intersection and the other velocity was calculated based on the premise that the follower has to brake and stop at the intersection. Both velocities were then stored while the intersection was alerted that the follower is approaching.
- The vehicles continued on the next lane along the same route or stop, given that the observed lane length sum is larger than the braking distance.

Once these steps have been executed on all vehicles, the intersection’s right-of-way rules are then applied in order to determine the vehicles that are allowed to pass over and the correct order of passage.

2.9.2 SUMO LANE-CHANGING MODELS.

The lane changing model used in SUMO is such that calculates an acceptable path in the network that can be used to complete the route. SUMO does this by evaluating the lane the follower is currently running on and the other lanes along its route and collects information about the distance the follower can continue using the lane without any need of changing into another lane and the occupancy of the other lanes. So with this information SUMO decides if there would be a need for a lane change or not.
SUMO assumes a distance that would be needed for a lane change. The distance is between the follower and the position on the lane in which the route cannot be continued and it is computed by equation 29:

\[
d_{lv}(t) = \begin{cases} 
V_v(t) \cdot \beta_1 + 2l_v & \text{if } V_v(t) \leq V_t \\
V_v(t) \cdot \beta_2 + 2l_v & \text{Otherwise}
\end{cases}
\]  

(29)

Where:
- \(d_{lv}(t)\) = the distance (m) assumed that a vehicle ‘v’ needs to change a lane in time ‘t’
- \(V_v(t)\) = the speed of vehicle ‘v’ at a time ‘t’ (m/s)
- \(V_t\) = threshold discriminating highway and urban behavior (m/s) set to a value of 14 m/s
- \(\beta_1, \beta_2\) = scaling factors which are set to 5 s and 15 s
- \(l_v\) = length of vehicle ‘v’ (m).

To evaluate the driver’s desire to advance forward quickly, a model based on Ehmans [85] was used. In this model, the difference between the safe speed on the adjacent lanes and the current lane is calculated by using the car-following model and then normalized by the maximum safe velocity the vehicle could travel with under an unrestricted flow of traffic. The difference calculated is referred to as the “advantage gained” by a vehicle in changing to another lane. This is illustrated in equation 30.

\[
A_l(t) = \frac{(V_p(t, l_a) - V_p(t, l_c))}{V_m(l_c)} 
\]

(30)

Where:
- \(A_l(t)\) = advantage gained by a vehicle in changing to lane \(l_a\) at time \(t\)
- \(l_a\) and \(l_c\) = the adjacent lanes and the current lanes
- \(V_p(t, l)\) = the safe velocity (m/s) a vehicle can be driven on lane \(l\) and at time \(t\).
- \(V_m(l)\) = the maximum velocity (m/s) at free flow with which a vehicle can travel on lane \(l\).

If the advantage gained in changing to another lane is positive, then the lane change would be executed but if the advantage gained in changing to another lane is negative, it implies that the current lane is faster that the adjacent lane and hence the desire to change lane would not be granted.
2.10 SUMMARY

Though un-signalized intersections are the more common type of intersections when compared with signalized intersections, they offer little control mechanism and not very effective in controlling and minimizing delays at intersections. To reduce delay at an intersection, there is a need that the intersection be signalized and further optimization of delay can be achieved by introducing transit priority systems at the intersection.

Although there are several variables that can be used as MOE of an intersection, delay is still the most effective because it relates to the amount of lost travel time, fuel consumption, and the frustration and discomfort of drivers. There are several models that are used to estimate delays at an intersection some of which are the Webster’s delay model, Akcelik delay model, the highway capacity manual (HCM) delay model, Australian delay model, Canadian delay model, the TRANSYT8 etc. It is desired that a bus experience least delay at an intersection and this can be achieved by using the appropriate TSP system that best suit the behavior of the overall traffic at the intersection.

Most effective BRT systems around the world like the Curitiba RIT system, Los Angeles Orange line and the Transmilenio BRT system made use of traffic signal actuations along the bus ways which gives priority to the bus at signalized intersection.
CHAPTER 3: METHODOLOGY

3.1. INTRODUCTION.

The methods used in measuring the delay experienced by buses on a signalized bus-only route intersection were explained in this chapter. The result of the proposed delay model was compared with results of other existing models. The chapter also included the method that was employed to study the effect of active prioritization of buses at signalized intersections. This chapter aimed at proposing a model that measured delay experienced by buses along bus-only route signalized intersections and also discussed the modelling procedures that were used to compare the effect of active prioritization at signalized intersections with the effect of un-prioritized intersections.

3.2. TOTAL TRAVEL TIME MEASUREMENT.

The total travel time of the bus was measured by boarding the bus from the selected starting point to the selected destination. Park station to Bosmont station was selected which is along the T3 trunk as shown in figure 3.2. This was because not all the intersections along the T3 route were signalized, some intersections were not signalized. However, all intersections between the selected points were signalized. While on-board, the time spent at each signalized intersection was recorded as well as the dwell time at each bus station. At each signalized intersection, the timing starts when the bus has come completely to a halt and stops when it starts moving again. Figure 3.1 shows the chat that was used for the recording of the delay at signalized intersections and dwell time at bus stations.

Several trips were made from Monday- Thursday. The field measurement captured total travel time at different periods of the day i.e. morning peak, off-peak and evening peak periods (the time selected for the peak periods was as mentioned in section 1.7). The travel time results from the trips are shown and explained in section 4.2 to section 4.4.
### REA VAYA DELAY MEASUREMENT CHAT.

**TIME OF TAKE OFF:** __________

**TIME OF ARRIVAL:** ____________

**DATE:** ______________________

---

<table>
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<th>TS2</th>
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<td>BS0</td>
<td></td>
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</tbody>
</table>

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**Total Distance of Trip:** 10.88 km / 6.76 mi

Figure 3.1. Field Measurement chat

---

Where BS represent Bus stations (0-12)

BS0 is the Park Station Bus station

BS12 is the Bosmont Station.

TS represent Traffic Signals (1-35).

AG...........Always green
RLR ........Red Light Running
0..............For no delay
x ............Not working
Figure 3.2. Bus stations and route along which travel measurement was taken
3.3 PROPOSED DELAY MODEL FOR BUS ONLY ROUTE.

A three term delay model was created which was;

\[ d = SST + DT + AT \]  (31)

Where:
\[ d = \text{delay of bus in seconds} \]
\[ SST = \text{Stop sight time} \]
\[ DT = \text{delay measured when bus is fully stopped} \]
\[ AT = \text{Acceleration time} \]

Each term of equation 31 were explained in details in the next section.

3.3.1 Stop Sight Time.

Delay of buses actually starts when the driver sights the signals from the traffic lights and starts to decelerate until the bus comes to rest. ‘Stop sight time’ is the term that was used to describe the time it took for the bus driver to perceive the signal, react to the signal and decelerate the bus till it came to a final stop. Equation 32-40 gives a detailed derivation of the stop sight time. Figure 3.3 shows a graphical illustration of the SST components.

\[ \frac{1}{2}mv^2 = s * \mu R \]  (32)

But \( R = w = mg \)

\[ \frac{1}{2}mv^2 = s * \mu mg \]  (33)

\[ s = \frac{v^2}{2\mu g} \]  (34)

But the stop sight distance \( S \) also involve the lag distance.

Therefore,
\[ s = vt + \frac{v^2}{2\mu g} \]  

(35)

To include the effect of gradient or slope of bus route,

\[ (\mu w + \frac{w}{100} z) s = \frac{wu^2}{2g} \]  

(36)

\[ s = \frac{v^2}{2g(\mu \pm 0.01z)} \]  

(37)

From equation (31) and (33)

\[ s = vt + \frac{v^2}{2g(\mu \pm 0.01z)} \]  

(38)

\[ SST = \frac{S}{V} \]  

(39)

\[ SST = t + 0.139 \left[ \frac{v}{g(\mu \pm 0.01z)} \right] \]  

(40)

Where:

\( SST = \) Stop sight time

\( K.E = \) kinetic Energy of bus.

\( \mu R = \) Frictional force.

\( s = \) distance travelled by bus

\( m = \) mass of the bus

\( w = \) weight of the bus

\( t = \) perception + the reaction time (varies from 1.5 sec to 2.5 sec)

\( v = \) design speed of the ‘bus only’ route (km/hr.)

\( g = \) acceleration due to gravity (9.8 m/s\(^2\))

\( \mu = \) coefficient of static friction between the bus tires and the road surface.

\( z = \) gradient of the corridor (+ when it is a rise, - when it is a fall)
3.3.2. Delay Measured When Bus is fully stopped (DT)

DT is the delay experienced at the intersection when bus has fully come to a stop. Equation 41-50 gave the DT value. Figure 3.4 shows the illustration of the stopped delay at the intersection.
From the Graph,

\[ x_1 = \frac{C - G}{h} + 1 \]  \hspace{1cm} (41)

\[ x_2 = \frac{C - G}{h} + 1 + X \]  \hspace{1cm} (42)

\[ x_3 = \frac{C - G}{h} + 1 + X \]  \hspace{1cm} (43)

Let \( K = \frac{C - G}{h} + 1 \)  \hspace{1cm} (44)

Therefore,

\[ C - G = h (K - 1) \]

Let \( x_3 = S \).

Therefore,

\[ G_t = \frac{K + X}{S} \]  \hspace{1cm} (45)

But \( x_1 = x_2 \) The same gradient value

\[ \frac{K}{h (K - 1)} = \frac{K + X}{h(K - 1) + \frac{K + X}{S}} \]  \hspace{1cm} (46)

Making \( X \) the subject formula

\[ X = \frac{Sh - K}{1 + \frac{Sh}{K}} \]  \hspace{1cm} (47)

Cumulative Delay is the area of the triangle

\[ \text{Cumulative delay} = 0.5 (C - G) \left( K + \frac{Sh - K}{1 + \frac{Sh}{K}} \right) \]  \hspace{1cm} (48)

Delay at Intersection (DT) = Equation 17 divided by \( K \)
\[ DT = 0.5 \left[ C - G \right] \left[ 1 + \left( \frac{sh}{k} - 1 \right) \right] \] (49)

\[ s = \frac{x}{\frac{G}{C}} \] (50)

Where:

\( DT \) = delay measured when bus is fully stopped

\( C \) = Cycle length of signal

\( G \) = Green time length of the signal

\( G_t \) = proportion of green time during which arrival rate equals departure rate

\( h \) = bus only route headway (seconds)

\( s \) = saturation flow rate of bus only route

\( x \) = capacity of the bus only route

3.3.3. Acceleration Time (AT)

AT is the term used to refer to the time it took for the bus to accelerate from rest to the design velocity of the road (which is also assumed to be the velocity the bus would travel if there was no delay at the intersection). Equation 50-52 gave the acceleration time value. Figure 3.5 illustrates the total delay experienced by the bus at a signalized intersection

The forward thrust of the bus neglecting air resistance = \( \frac{Power}{Velocity} \) = Thrust

\[ \frac{PWR \times w}{v - u} = Thrust \]

\[ \frac{PWR \times w}{v - u} = \frac{w}{g} \left( a \right) + w \left( 0.01z \right) \] (50)

Making “\( a \)” the subject formula from (20) gives;
\[ a = \frac{g^{\cdot PWR}}{v-u} - g(0.01z) \] (51)

But \( AT = \frac{v-u}{a} \)

Therefore \( AT = \frac{(v-u)^2}{0.0772 g(PWR - 0.01z(v-u))} \) (52)

AT = Acceleration time

\( v = \) design velocity of the facility in km/hr

\( u = \) initial velocity of the bus (taken to be zero, unless the bus did not stop fully before it begins to accelerate).

PWR = power to weight ratio of the bus in consideration

\( w = \) weight of bus

\( z = \) gradient of the corridor (+ when it is a rise, - when it is a fall)

\( g = \) acceleration due to gravity (9.8m/s\(^2\))

Figure 3.5: An illustration of the total delay experienced by bus at a signalized intersection.
3.4 BUS STATION LOCATION EFFECT ON MODEL.

The bus went through a cycle at the sight of a stop signal from a signalized intersection. As shown in figure 3.6, the cycle involved

- Deceleration of the bus from the design speed of the road facility. Marked as 1 in Figure3.6.
- The bus came to a full stop. Marked as 2 in Figure3.6.
- The bus accelerated from rest back to the design speed of the facility at the end of the red time. Marked as 3 in Figure3.6.

There would be a little change to this cycle due to the position of bus stations relative to the signalized intersection. The bus station could be far side or near side.

![Graphical representation of the cycle a bus went through at the sight of a stop signal.](image)

Where:

- \( V \) = design speed of the facility
- \( d \) = total delay of bus because of un-prioritized intersection

Figure3.6. A graphical representation of the cycle a bus went through at the sight of a stop signal.

3.4.1 Far Side Bus Station.

For designs where bus stations were located after an intersection (just some meters after the intersection), the journey cycle of the bus at the sight of a stop signal differed a little from that in figure 3.7. The journey cycle became:
- Deceleration of the bus from the design speed of the road facility. Marked as 1 in Figure 3.7.
- The bus came to a full stop. Marked as 2 in Figure 3.7.
- The bus accelerated from rest back to a speed \(v^*\) less than the designed speed of the facility (and stopped again at the bus station). Marked as 3 in Figure 3.7.

### 3.4.2 Near Side Bus Station

For designs where bus stations were located before an intersection (just some meters before the intersection), the journey cycle became:

- Acceleration of the bus from rest to \(V^*\). Marked as 1 in Figure 3.8.
- The bus came to a stop. Marked as 2 in Figure 3.8.
- The bus accelerated from rest back to the design speed of the facility. Marked as 3 in Figure 3.8.
The delay model for the far side and the near side bus station location became:

- **Far side bus station location**
  
  From equation 31,
  
  \[
  \text{delay} = \text{SST} + \text{DT} + \text{AT}
  \]

  SST, DT retained the same equation as seen in equation 40 and 49 respectively but AT became:

  \[
  \text{AT} = 0.0772 \frac{(v * -u)^2}{PWR} \pm 0.01(zg)(v * -u)
  \]  

  (53)

  Where:

  \begin{align*}
  \text{AT} &= \text{Acceleration time} \\
  v^* &= \text{speed attained just before stopping at bus station}
  \end{align*}

The approximate path the bus would have followed if the intersection was prioritized (zero delay).
u = initial velocity of the bus (taken to be zero, unless the bus did not stop fully before it begins to accelerate).

PWR = power to weight ratio of the bus in consideration

z = gradient of the corridor (- when it is a rise, + when it is a fall)

g = acceleration due to gravity (9.8m/s²)

- Near Side bus station location.

From equation 31,

\[ delay = SST + DT + AT \]

But because the bus accelerates from rest at bus station to a speed \( v^* \) and only stops at the signalized intersection which is just about 50 meters from the station, the SST term of the equation was taken to be approximately zero since the bus would still have to go through the initial acceleration to speed \( v^* \) even if the intersection was prioritized. So the terms that accounted for the bus delay are; the delay caused by a full stop and the delay caused by acceleration to the design speed of facility.

The delay at near side bus station location was:

\[ delay = DT + AT \]

Where DT and AT retain their already stated meaning and values.

3.5 DATA COLLECTION.

On site data collection was carried out on different types of intersection and complexities. Google map helped with identifying the intersections by providing a view of what the intersection looks like which facilitated the choice of the intersection picked. All intersections are along the BRT bus corridor and hence have the bus only routes.

About ten intersections were selected. The proposed model was then used to calculate the delay experienced at the selected intersections. Selection was such that includes different types of intersection (i.e. the T, Skewed T, right angle and the oblique). Figure 3.9 to 3.17 shows the name,
the type, the length of signal cycle, green time of bus lane (which was necessary to calculate the
designed capacity of the bus lane) and complexity of the intersections that were selected. Table
3.1 shows each intersection against their length of signal cycle and the allocated green time for the
bus only lane.

Figure 3.9 Melville/ Sophia Intersection.

Type of Intersection: Right angles
Complexity of Intersection: 4 legs
Length of Signal Cycle: 120 sec.
Green time for bus only lane: 41 sec.

Figure 3.10 Stanley Avenue/ Annet Road Intersection.

Type of Intersection: Skewed T
Complexity of Intersection: 4 legs
Length of Signal Cycle: 70 sec.
Green time for bus only lane: 42 sec.
Figure 3.11 Perth Road/ Lewes Road Intersection.

Type of Intersection: T
Complexity of Intersection: 3 legs
Length of Signal Cycle: 70 sec.
Green time for bus only lane: 28 sec.

Figure 3.12 Harmony Street/ Main Road Intersection.

Type of Intersection: Right angle
Complexity of Intersection: 4 legs
Length of Signal Cycle: 99 sec.
Green time for bus only lane: 17 sec.
Figure 3.13 Hay Avenue/ Harmony Street Intersection.

Type of Intersection: Oblique
Complexity of Intersection: 4 legs
Length of Signal Cycle: 100 sec.
Green time for bus only lane: 57 sec.

Figure 3.14 New Canada Road/ Main Reef Road

Type of Intersection: Right angles
Complexity of Intersection: 4 legs
Length of Signal Cycle: 100 sec.
Green time for bus only lane: 36 sec.
Type of Intersection: Oblique
Complexity of Intersection: 4 legs
Length of Signal Cycle: 109sec.
Green time for bus only lane: 31 sec.

Figure 3.15 Empire Road/ Jan Smuts Avenue

Type of Intersection: Right angles
Complexity of Intersection: 4 legs
Length of Signal Cycle: 110sec.
Green time for bus only lane: 7.2 sec.

Figure 3.16 Empire Road/ Victoria Avenue Intersection.
Type of Intersection: Right angles
Complexity of Intersection: 4 legs
Length of Signal Cycle: 69 sec.
Green time for bus only lane: 29 sec.

75.14 meters

Type of Intersection: Right angles
Complexity of Intersection: 4 legs
Length of Signal Cycle: 69 sec.
Green time for bus only lane: 23 sec.

Figure 3.17 Rissik/ Smit and Rissik/ Wolmarans Intersection
Table 3.1. Intersections showing the allocated green time portion.

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<th>Name of Intersection</th>
<th>Length of signal cycle. ‘C’ (seconds)</th>
<th>Green time for bus only route. ‘g’ (seconds)</th>
<th>Complexity of Intersections</th>
<th>g/c</th>
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<td>120</td>
<td>41</td>
<td>4 legs</td>
<td>0.34</td>
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<tr>
<td>Stanley Avenue/ Annet Road Intersection</td>
<td>70</td>
<td>42</td>
<td>3 legs</td>
<td>0.6</td>
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<td>70</td>
<td>28</td>
<td>3 legs</td>
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<tr>
<td>Harmony Street/ Main Road Intersection.</td>
<td>99</td>
<td>17</td>
<td>4 legs</td>
<td>0.17</td>
</tr>
<tr>
<td>Hay Avenue/ Harmony Street Intersection</td>
<td>100</td>
<td>57</td>
<td>4 legs</td>
<td>0.57</td>
</tr>
<tr>
<td>New Canada Road/ Main Reef Road</td>
<td>100</td>
<td>36</td>
<td>4 legs</td>
<td>0.36</td>
</tr>
<tr>
<td>Empire Road/ Jan Smuts Avenue Intersection</td>
<td>109</td>
<td>31</td>
<td>4 legs</td>
<td>0.28</td>
</tr>
<tr>
<td>Empire Road/ Victoria Avenue Intersection</td>
<td>110</td>
<td>7.2</td>
<td>4 legs</td>
<td>0.065</td>
</tr>
<tr>
<td>Rissik/ Smit Intersection</td>
<td>69</td>
<td>29</td>
<td>4 legs</td>
<td>0.42</td>
</tr>
<tr>
<td>Rissik/ Wolmarans Intersection</td>
<td>69</td>
<td>23</td>
<td>4 legs</td>
<td>0.33</td>
</tr>
</tbody>
</table>

3.5.1 FIELD WORK.

The dates for the field work were selected in a way to avoid any major holiday celebration and not at the end of the year or at the beginning when there were more travels. The data collection was done from February to May 2017 by researchers at the University of Johannesburg. Two peak periods were considered; The Morning peak and the afternoon peak. The morning peak was from 7-9 am and the afternoon peak was from 4-6 pm and data was collected from Monday –Thursday for optimum result. The field work was carried out for the following reasons:

- To measure the delay experienced by the bus at the traffic signals, the dwell time at bus stations and the total travel time at peak and off-peak periods. Researchers were provided with the Reavaya delay measurement chat as seen in Figure 3.1 and the data collected was then fed into the delay model already discussed in this chapter and other delay models i.e.
the HCM field model and the Canadian model. Their results (delay measured) was discussed in the following chapter.

- To measure the green time, cycle length, phase sequence, phase length and other traffic signal attribute along the selected corridor. This was used to calibrate the modelling done in SUMO.

The field work was done with the researchers boarding the buses and with the use of a stopwatch and a pen, their observations were recorded into the measurement chat in Figure 3.1. Several turns were done so as to bring error to the minimum. The second part of the field measurement was done by researchers observing each intersection along the selected bus corridor and recording the traffic signal attribute (i.e. cycle length, green time etc.) and all other traffic attributes described in section 3.6.1. This was done several times so as to minimize errors.

Results from field measurement and observation were fed into SUMO and then simulated. The simulation is an imitation of the exact flow of traffic along the chosen BRT corridor. The results of the simulation exercise were explained in section 4.8

3.6 MODELLING IN SUMO.

Simulation of Urban Mobility (SUMO) version 0.29.0 was used for the simulation. The software was used to simulate the existing condition on the Reavaya corridor. A section of the BRT corridor that extends to 1.37km and includes 5 signalized intersection was selected for the simulation as shown in figure 3.18, 3.19 and 3.20. The section of the BRT corridor simulated was chosen because the corridor exhibits the interaction that exist between the BRT buses and other vehicles. The intersections along the corridor includes 2 four-arm intersections with right turns, 2 three-arm intersections and a multi-approach intersection. The following are the reasons why Simulation of Urban Mobility (SUMO) Software was chosen for the simulation exercise [86] [87] [88].

- The software offers a microscopic road network and traffic simulation which has ability to handle large and complex networks.
- It allows the importation of networks or maps from openstreetmap, VISUM, Vissim, MATsim, and ArcView. This makes the network modelling to be more accurate and precise.
Figure 3.18 The BRT Corridor Network Diagram as generated from SUMO.

Figure 3.19 The BRT corridor selected as generated from SUMO during simulation showing the intersections.
It allows for vehicle and vehicle type definitions (e.g. bus, cargo, trucks, passenger, trams etc.) and also allows the routes of the vehicles to be defined by the user.

It allows for actuation of traffic lights based on time gaps or time loss. This makes the prioritization of the bus only lane to be easily done.

The output of the simulation includes positions and velocities of all vehicles in the simulation at a particular time, positions of a certain type of vehicle (e.g. bus) over time, emission values of all vehicles in the simulation at a particular time, waiting time, queue length at an intersection and the average trip duration.

This simulation was done by defining each vehicle and bus properties. The properties defined include the lanes that were used by the buses and other vehicles, the velocity, pollutant and emission properties. The emission class that was used for the buses are those described by the HBEFA for a diesel driven heavy duty vehicle (EURO norm 4) [89-91].
SUMO simulations has a standard step-length of 1 second and the vehicle’s position is determined by the lane on which the vehicle is running and its distance from the beginning of the lane [92-94]. The vehicle’s speed was calculated by using a car following model that was developed by Stefan Kraub [95].

3.6.1 DATA COLLECTION DETAILS AND SCOPE

The data used for this modelling includes four major groups they are; the geometric attribute of corridor, the traffic attribute of the corridor, the signal control of all intersections along the corridor and transit information of bus and the other vehicles.

The data used to describe the geometric attribute of corridor includes number of lanes of the bus-only route and the general traffic, the length of the corridor, the markings on the pavement for both bus lanes and the general traffic lanes, the different grade levels along the corridor, section of the pavement marked for aesthetics (planted flowers) and positions of vertical and horizontal curves along the corridor.

The data used to describe the traffic attribute of the corridor includes position of reduced speed areas along the corridor, number of buses along the corridor per hour, number of vehicles travelling along the corridors per hour with their directions, number of vehicles turning per hour and the speed distributions of both buses and other vehicles.

The data used to describe the signal control of the corridor includes the green times of each signal along the corridor, the length of clearance of each signal along the corridor, the cycle length of each signal along the corridor, the minimum green times, the maximum green times, phase length of the different phases, phase sequence at each intersection and positions of intersection with yield signs.

The data used to describe the transit information of bus and other vehicles include the headway of the bus, the spacing of the bus, arrival rate of the vehicles along the general traffic and the different routes for the bus and the general traffic.

The source of the data used for the modelling is shown in table 3.2
Table 3.2 Data used for the modelling and the sources of the data.

<table>
<thead>
<tr>
<th>Data description</th>
<th>Source of Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometric attribute of the corridor</td>
<td>Imported file from openstreetmap</td>
</tr>
<tr>
<td>Traffic attribute of the corridor</td>
<td>Field observation and measurement</td>
</tr>
<tr>
<td>Signal control of the corridor</td>
<td>Field observation and measurement</td>
</tr>
<tr>
<td>Transit information of bus and vehicles</td>
<td>Reavaya bus schedules and field measurement</td>
</tr>
</tbody>
</table>

3.6.2 DATA VALIDATION.

During modelling, the operating speed of the bus along the corridor was made to be close to the operating speed of the bus in real life scenarios. The bus operating speed along the corridor in real life scenario ranges from 23km/hr to 33.42 km/hr (from table 4.1; transit time for 11km) and the generated travelling speed from the simulations using SUMO gives 30.4 km/hr which is a result that is within the travelling speed of the bus. It is also to be noted that most of the input to the modelling was acquired from direct field observations and measurement (described in section 3.5.1) which also makes the output of the simulations to be close to real life scenarios.

The signal timing as seen during modelling was close to the existing signal timing at the intersections under study and special care was taken to make sure the phase sequence were the same as the real life scenarios.

For the prioritization, SUMO allows a particular lane or traffic direction to be given priority over the other lanes or directions by simply picking the option on its tool bar. Therefore that lane acts like it is actively prioritized in real life scenarios. The simulation was first done with the option deactivated and hence the simulation follows the exact loaded signal timings and afterwards the simulation was run with the lane-prioritization option activated.

3.7 SUMMARY

The methods used in measuring the delay experienced by buses on a signalized ‘bus only’ route intersection as well as the method that was employed to study the effect of active prioritization of buses at signalized intersections were explained in this chapter. A delay model that measured delay experienced by buses along bus-only route signalized intersections was also proposed. A description of the data that was used for the modelling of the effect of active prioritization as well as a brief discussion about the software employed for the modelling was given in this chapter.
CHAPTER 4: RESULT AND DISCUSSION

4.1 INTRODUCTION

This chapter discussed the result of the study that was carried out on the selected section of the Reavaya bus-only lane trunk. The selected trunk was about 11km long and transverse 33 signalized intersections. The chapter also discussed the result showing the effect of intersection complexity and geometry on delay and also discussed the effect of active prioritization at signalized intersections along the bus-only route.

4.2 TRAVEL TIME ELEMENTS OF REAVAYA BUS RAPID TRANSIT EXAMINED.

The average travel time and its elements (time in transit, control delay, dwell time at bus stations) is shown in figure 4.1.

![Figure 4.1 showing travel time elements](image)

Figure 4.1 how the travel time elements add up to make the total travel time.

The figure reveals that about 22% of the transit time is spent at the intersection and 15% as dwell time and the rest of the time is spent in transit.
4.2.1 TRAVEL TIME ELEMENTS ANALYSED BY PERIOD OF THE DAY.

Three periods were examined which are the morning peak (also the a.m. peak), the off-peak and the afternoon peak (also the p.m. peak) periods. Table 4.1 as well as Figure 4.2 shows the mean value of the travel time elements for different times of the day.

Table 4.1 Mean Values of Travel time elements for different time of the day

<table>
<thead>
<tr>
<th>Travel Time Elements</th>
<th>Mean Travel time Elements (min: sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AM Peak</td>
</tr>
<tr>
<td>Control Delay</td>
<td>6:41</td>
</tr>
<tr>
<td>Dwell Time</td>
<td>4:48</td>
</tr>
<tr>
<td>Transit time</td>
<td>17:41</td>
</tr>
<tr>
<td>Total mean travel</td>
<td>29:10</td>
</tr>
</tbody>
</table>

Figure 4.2 mean value of the travel time elements for different times of the day.
Table 4.1 as well as Figure 4.2 show that dwell time of bus is higher at peak times. This is expected as there were more commuters and hence more time for boarding and alighting. The afternoon peak has the highest time in transit as well as control delay this shows that the effect of non-prioritization of buses at the intersection is most obvious at the afternoon peak times. It is also well noticed that the average control delay is lowest at the off peak periods this is largely because of the less pressure on the general traffic which encourages the drivers to run the red light at chance. The occurrence of red light running is more common during off-peak period than during peak-periods as shown in figure 4.3. Figure 4.4 is a Red-light running case captured at an off-peak period (11:12 am).

Figure 4.3 Comparison of Red-light running cases during the peak and the off-peak periods.

Figure 4.4 A case of red-light running
4.2.2 TRAVEL TIME ELEMENTS ANALYSED BY DIRECTION OF TRAVEL.

The two direction of travel are the Park-Station bound travel and the Bosmont-station bound travel. Figure. 4.5 shows the travel time elements analyzed by direction which reveals that the difference between Bosmont station bound and the Park station bound is the control delay experienced which is more for the Bosmont station bond probably because of the slight difference in the route. The travel time was further analyzed by direction of travel and also by the time periods of the day as shown in figure 4.6.

Figure 4.5 Average Travel time elements analyzed by direction of travel.
Table 4.2 and Table 4.3 show the comparison of the travel time elements for Bosmont station bound and Park station bound respectively.

<table>
<thead>
<tr>
<th>Travel Time Elements</th>
<th>Mean Travel time Elements (min: sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AM Peak</td>
</tr>
<tr>
<td>Control Delay</td>
<td>7:43</td>
</tr>
<tr>
<td>Dwell Time</td>
<td>4:43</td>
</tr>
<tr>
<td>Transit time</td>
<td>17:10</td>
</tr>
<tr>
<td>Total mean travel</td>
<td>29:36</td>
</tr>
</tbody>
</table>

Figure 4.6 Travel time analyzed by direction of travel and also by the time periods of the day.
Table 4.3 Park-station bound mean values of travel time elements for different time of the day

<table>
<thead>
<tr>
<th>Travel Time Elements</th>
<th>Mean Travel time Elements (min: sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AM Peak</td>
</tr>
<tr>
<td>Control Delay</td>
<td>5:40</td>
</tr>
<tr>
<td>Dwell Time</td>
<td>4:55</td>
</tr>
<tr>
<td>Transit time</td>
<td>18:12</td>
</tr>
<tr>
<td>Total mean travel time</td>
<td>28:47</td>
</tr>
</tbody>
</table>

4.3 COMPARISON OF THE REAVAYA TRAVEL TIME WITH OTHER BRTs

The study focused on a section of the T3 trunk of the Reavaya. The section was studied because it has most of its intersections signalized. The other part of the trunk has its intersection un-signalized. However, the whole trunk is about 23.59km (Library garden to Thokoza Park) and it takes an average of 50 minutes 33 seconds to complete the Journey. This shows an increase of about 43% from travel time of the Los Angeles Orange line that travels 29km in an average of 43 minutes and 31 seconds [96] and about 48% increase from travel time of the Beijing Southern Axis BRT line 1 that travels 15.8 km in 37 min [97].

4.4 OBSERVED EFFECTS OF PLATOONING

1. Platooning of buses becomes more obvious at peak times as seen in figure 4.7. This is a direct result of un-prioritization of signalized intersection as increased frequency of bus without a good control at intersections would lead to bus platooning.

2. Platooning causes increased dwell time at bus stations especially for the trailing bus. Since some bus stations are designed to service a maximum of two regular buses at a time, there is usually a queue of buses at the station during peak periods if there is one or more articulated buses involved as seen in figure 4.8.
3. Platooning of buses during peak period can become an advantage at bus stations (stations with two alighting points) when the platooned buses are going to the same destination. This
is because boarding and alighting of passengers become faster since two buses are available at once.

4.5 COMPARISON OF DELAY MEASUREMENT METHODS.

Table 4.4 shows the result of average delay experienced by the Reavaya buses at the named intersections at peak periods as measured by the model proposed, Canadian model and the field measurement. The field measurement delay values were recorded by traffic enumerators in the Reavaya buses.

Table 4.4 Average delay experienced by a bus at signalized intersection measured by using the Field measurement technique, the Canadian model and the proposed model

<table>
<thead>
<tr>
<th>Name of Intersection</th>
<th>Average Field Measurement (sec)</th>
<th>Average Delay as calculated by model</th>
<th>Canadian Model (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SST (sec)</td>
<td>DT (sec)</td>
<td>AT (sec)</td>
</tr>
<tr>
<td>Melville/Sophia</td>
<td>39.49</td>
<td>3.07</td>
<td>40.78</td>
</tr>
<tr>
<td>Lewes/Perth road</td>
<td>21.78</td>
<td>3.34</td>
<td>29.76</td>
</tr>
<tr>
<td>Rissik/ Wolmarans</td>
<td>18.98</td>
<td>2.76</td>
<td>32.71</td>
</tr>
<tr>
<td>Rissik/smith</td>
<td>18.55</td>
<td>2.93</td>
<td>28.33</td>
</tr>
<tr>
<td>Empire/Jan Smith</td>
<td>41.93</td>
<td>3.25</td>
<td>42.48</td>
</tr>
<tr>
<td>Harmony street/main road</td>
<td>40.20</td>
<td>3.30</td>
<td>44.78</td>
</tr>
<tr>
<td>Stanley Avenue/Annet Road</td>
<td>36.22</td>
<td>3.19</td>
<td>35.73</td>
</tr>
<tr>
<td>Hay Avenue / Harmony street</td>
<td>23.41</td>
<td>3.20</td>
<td>30.46</td>
</tr>
<tr>
<td>Empire road/Victoria avenue</td>
<td>46.00</td>
<td>3.19</td>
<td>46.47</td>
</tr>
</tbody>
</table>

Where:

SST is the delay component responsible for bus deceleration from its normal travel speed.

DT is the delay component that measures the actual stop-time at the intersection.

AT is the delay component responsible for bus acceleration back to its normal travel speed.
The table shows that the delay measured by using the proposed model have the highest value for all intersections. The reason being that it includes the delay value caused by the deceleration of the bus as it approaches the intersection and the acceleration of the bus to its travel speed as it crosses the intersection.

Figure 4.9 shows a comparison between the DT component of the proposed model and the field measurement.

The figure shows that there is little variation (the difference can be as low as 1%) between the DT component of the proposed model (the component of the proposed model that measures the actual stop-time of the bus at the intersection) and the actual field measurement. However it can be noticed that the largest variation exist at Rissik/Wolmarans and Rissik/Smith intersections. This is as a result of the following:
The Rissik/Wolmarans intersection is a far side intersection (i.e., it is located just 26.95 metres from the bus station (Park station Bus station)). When the traffic signal is a red, the bus driver (who also has a clear sight of the traffic signals) would rather increase his dwell time at the bus station or travel to the intersection with the possible least speed to avoid stopping at the intersection. Hence reducing to a great degree the delay he experiences at the intersection.

The distance between Rissik/wolmarans and Rissik/Smith intersection is very short (about 75m) which makes the behavior of the driver at the intersection to be inconsistent. He may decide to wait for signals at both intersections to be green before leaving one intersection for the other so as to avoid sharp breaking at the latter intersection. Section 4.6 discusses the minimum distance between intersections that could be used when designing a BRT lane.

Figure 4.10 shows a comparison between the total value of delay as measured by the model (SST + DT + AT) and the delay recorded from the field evaluation.

![Figure 4.10 Comparison of Delay values as measured by the proposed Model and the field.](image)

From Figure 4.10 it can be seen that there is a large variation between the total delay as measured by the model and the field measurement result (minimum of 10 seconds difference).
The difference reveals that deceleration and acceleration of the bus is a factor to consider in other to measure delay at signalized intersection effectively.

Figure 4.11 shows a comparison between the field measurement and the Canadian model.

![Graph showing comparison between field measurement and Canadian model](image)

**Figure 4.11 Comparison of field measurement and Canadian model**

Delays at intersection as measured by the Canadian model have a lower value than those of the field measurement. This is because Canadian model measures delay in two parts which are: the uniform delay and the overflow delay. The first term of the Canadian model measures the uniform delay and the second term the delay as a result of overflow. Overflow or cycle failure does not exist in a bus only route. Hence, only the first term of the equation can be used (which measures uniform delay only). It should be noted that the first term of Canadian model, HCM and the Akcelic model is the same. Therefore they all have the same delay value for a bus only route. It should also be noted that the Canadian, HCM and Akcelic models do not include the extra delay incurred by deceleration and acceleration of the bus.

Figure 4.12 shows a comparison between the three methods that have been used in this project to measure delay of buses at a signalized intersection.
It is obvious from the graph that the delay values as measured by the proposed model are the highest of the three methods employed to measure delay. The proposed model is best used at peak periods when the headway of the buses are adhered to.

4.6 MINIMUM SPACING OF INTERSECTIONS ALONG BUS RAPID TRANSIT LANES.

From the field observations, it was observed that there were sharp braking when buses travelled between intersections that have very short distance between them. This was because drivers don’t have enough time for perception, reaction and navigation [98]. An example was the Rissik/Wolmarans and the Rissik/Smith intersections which has just 75 meters between them. It was also noticed that cases of red light running were very common at this site and thereby raises issues of safety. The transportation research board concluded that spacing at intersections plays a major role in operation efficiency and safety at intersections [99][100]. The Transportation research board recommends a minimum distance of 1,100ft which is about 350m [99]. However, a distance of 400m would be recommended based on the field survey done. It was noticed that a
distance of 400m would allow adequate time for perception, reaction and navigation for both articulated and non-articulated bus drivers.

4.7 ANALYSIS OF RESULTS TO SHOW THE EFFECT OF COMPLEXITY AND GEOMETRY OF INTERSECTION ON DELAY.

In other to study the effect of complexity and geometry of intersections on delay, the intersections with similar complexity were studied together and their performance compared with those of different complexity. The same method was used to study the effect of geometry of intersections on delay. The delay values used for the comparison were those from table 4.4

4.7.1 EFFECT OF NUMBER OF LEGS OF INTERSECTION ON DELAY.

Most of the intersections considered were four legs and three legs intersections. The average delay experienced by bus at three-leg intersections was compared with the average delay experienced by bus at four-leg intersections. From table 3.1, It can be seen that Melville/Sophia, Harmony street/main road, Hay avenue/Harmony street, Empire road/ Jan smuts, Empire road/ Victoria, Rissik/Smith, Rissik/Wolmarans are all four legs intersections while Stanley avenue/ Annet, Perth road/ lewes road are three legs intersection. Figure 4.13 shows a comparison between the average delay experienced at three-leg intersections and four-leg intersections.

Figure 4.13 Comparison between average delays experienced at three-leg intersections and at four-leg intersections.
As already discussed in section 2.7.1, the more the number of legs the more the number of conflicting points [52] and hence more delay is expected at intersections with more legs. Even though this is true with all the methods used to measure delay at intersections, it is also true that the difference in the delay can be said to be minimal; 1.8% difference as measured by the proposed model, 7.83% as measured by the Canadian model, 13% difference as measured during the field measurement.

**4.7.2 EFFECT OF SKEW AT INTERSECTIONS ON DELAY.**

The delay experienced by a bus at a three-leg intersection was compared with delay experienced at a skewed three-leg intersection. Figure 4.14 shows the result obtained when delay at Stanley avenue/Annet road intersection (a three-leg, skewed intersection) was compared with Perth road/lewes road intersection (a three-leg intersection)

![Figure 4.14 Comparison between average delays experienced at three-leg intersections and at three-leg skewed intersections.](image)

The delay experienced by a bus at a four-leg intersection was also compared with the delay experienced at a four-leg skewed intersection. Melville / Sophia intersection, Harmony Street/main road, Empire road/ Victoria Avenue are all four-leg intersections with no skew while Hay Avenue/harmony intersection, Empire road/ Jan Smuts Avenue are four-leg intersections with skew. The result of the comparison is shown in figure 4.15
From figure 4.14, it can be seen that skew can increase the delay experienced at a three-leg intersection. Othman C.P. et al estimated about 8.31% higher delay at skewed intersections [54] which is similar to the 3.8% increase in delay as measured by the proposed model. However, from figure 4.15, it was seen that skew did not increase the delay experienced at a four-leg intersection. The result shows that the intersections with skew present a lower delay. It can be concluded that though skew at an intersection may contribute to the delay at a three-leg intersection, it may not contribute to the delay at a signalized four-leg intersection but it is not safe to conclude that skew may reduce the delay experienced at intersections. The presence of signals at skewed intersections reduced the occurrence of accidents which may occur at an un-signalized skewed intersection as pointed out as FHWA [28] and thereby addressing safety concerns at skewed intersections that was raised by Hanna J.T. et al. [55].

4.7.3 EFFECT OF NUMBER OF LEGS OF INTERSECTION ON DELAY DURING OFF-PEAK PERIODS.

To investigate if the same pattern that occurred during peak periods also occur during off-peak periods, the same analysis was repeated for off-peak periods. The proposed model was not used to measure delay during off-peaks because it was discovered that there was a collapse of the bus headway during off-peak periods. The headways were not adhered to and were very random. This
will make measurements from proposed model to be erratic. Figure 4.16 shows a comparison between the average delay experienced at three-leg intersections and four-leg intersections.

![Comparison between average delays at three-leg and four-leg intersections](image)

**Figure 4.16** Comparison between average delays experienced at three-leg intersections and at four-leg intersections for off-peak periods.

From figure 4.16, it can be seen that the average delay at four-leg intersections is more than the average delay at three-leg intersections. Comparing figure 4.16 with figure 4.13 showed that at off-peak periods the difference between delay experienced at four-leg intersections and delay experienced at three-leg intersections becomes very large.

**4.7.4 EFFECT OF SKEW AT INTERSECTIONS ON DELAY DURING OFF-PEAK PERIODS.**

Figure 4.17 shows the result obtained when delay at Stanley avenue/Annet road intersection (a three-leg, skewed intersection) was compared with Perth road/lewes road intersection (a three-leg intersection) at off-peak period.
From figure 4.17, it was seen that the average delay experienced at three-leg intersection and at three-leg skewed intersection at off-peak periods is very close with little difference. This shows that the effect of skew at intersection on delay is very minimal at off-peak periods.

The delay experienced by a bus at a four-leg intersection was also compared with the delay experienced at a four-leg skewed intersection for off-peak periods and the result is shown in figure 4.18.

Figure 4.17 Comparison between average delays experienced at three-leg intersections and three-leg skewed intersections for off-peak periods.

Figure 4.18 Comparison between average delays experienced at four-leg intersections and at four-leg skewed intersections for off-peak periods.
From 4.18, a conclusion can be made that the average delay experienced at four-leg intersections is close to the average delay experienced at four-leg skewed intersections during off-peak periods as presented by the field measurements result. This is also true for three leg intersections (skewed and not skewed).

4.8 SUMO SIMULATION RESULTS.

To study the effect of prioritization of buses at signalized intersections, SUMO (version 0.29.0) was used to simulate the existing condition on a section of the BRT corridor (figure 3.17 and figure 3.18). The simulation was carried out first by using the signal timings that are being used by the traffic lights at the intersections. The buses operating condition while travelling along the selected corridor as well as the road network (i.e. lanes and edges) condition were then measured. The buses operating conditions measured during simulation include; the waiting time experienced by a bus during the journey as a result of delay at each signalized intersections (average value), the fuel consumed by a bus during the journey (average value), the amount of particulate matter released by a bus during the journey, the amount of CO$_2$, CO, HC and NOx released by a bus during the journey (average value).

The road network conditions measured include; the network travelling speed, the network occupancy (the degree to which a lane or an edge was occupied in %), the waiting time and the network speed (the speed in which a vehicle has to travel to exit the network giving the existing traffic condition).

The simulation was then repeated when the bus lanes were actively prioritized at signalized intersections. The number of the vehicles on the network during simulation was made to reflect the real world as much as possible. The results are presented in the following sections.

4.8.1 RESULT SHOWING EFFECT OF PRIORITIZATION ON BUS OPERATIONS.

For each simulation 7 buses travelled along the bus lane, the results displayed are the average values from the 7 buses.

Figure 4.19 compares the average travelling speed of the buses on the corridor selected when the signal at intersections was prioritized and when it was un-prioritized.
From figure 4.19, it can be seen that a bus has a higher travelling speed when the signal at intersections was prioritized. There was an increase of about 8km/hr when the intersection was prioritized similar to the result obtained in Vicenza in Italy where prioritization increased bus speed by 5km/hr [101]

Figure 4.20 compares the average waiting time of the buses at each intersection when signal was un-prioritized with when it was prioritized.

From figure 4.20, it can be seen that prioritization of buses along bus-lane at signalized intersections does not completely eliminate delays (or waiting time) at intersections but can reduce it to a great degree. In this case, the delay at signalized intersection was reduced by as high as 68%. The reduced delay at signalized intersections contributes to a decrease in the bus
travel time which was also the case at Lyon in France, Strasbourg in France and Stuttgart in Germany where a reduction of 11-14%, 4-5% and 50% of travel times were recorded respectively [102-104]. Similarly at Zurich, Switzerland, it was claimed that about 90% of signalized intersections do not have any waiting time for their bus rapid transit system [105].

Figure 4.21 compares the average fuel consumption rate (ml/sec.) of the buses as they travel along the selected corridor when the signal at intersections was un-prioritized and when it was prioritized.

Figure 4.21 shows a higher fuel consumption rate when intersections are un-prioritized. More fuel is consumed at the point the car accelerates from rest to its travelling speed.

Figure 4.22 shows comparison of the average total emissions from the buses when the signal at intersections was un-prioritized and when it was prioritized.
Figure 4.16 shows that prioritization of signals at signalized intersection for buses reduces emissions of pollutants (CO\textsubscript{2}, CO, HC, NOx and PMx) from the buses. 13% decrease in CO\textsubscript{2}, 17% decrease in CO, 12% decrease in HC, 15% decrease in NOx and 15% decrease in PMx. In a research conducted by Germa Bel, where he used real field data obtained from automatic air quality monitoring stations, it was concluded that the introduction of bus rapid transit system reduced CO concentrations by 16.6-20.4%, NOx by 12.9-18.1% and PMx by 20.8-39.0%. He also suggested that the introduction of bus priority system along the bus rapid transit route would further reduce emission of pollutants [106].

4.8.2 RESULT SHOWING EFFECT OF PRIORITIZATION ON ROAD NETWORK

Table 4.5 shows the effect of prioritization on the edges around the bus-lane. It should be noted that the value shown are average values over several simulations and edges do not include bus-lanes. Figure 4.17 and Figure 4.18 show the edges of the intersections under consideration.
Figure 4.23 Edges 1,2,3,4 from two different intersections

Figure 4.24 Edges 5,6,7,8 from two different intersections
Figure 4.25 Edges 9,10,11,12 and 13 from two different intersections

Figure 4.26 Edge 14
Table 4.5 Network performance measurement and comparison between prioritized intersections and un-prioritized intersections.

<table>
<thead>
<tr>
<th></th>
<th>Un-prioritized Intersections</th>
<th>Prioritized Intersections</th>
<th>% change</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Edge 1</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Travel time (sec)</td>
<td>26.1</td>
<td>27.8</td>
<td>+7</td>
</tr>
<tr>
<td>Occupancy (%)</td>
<td>30.2</td>
<td>36.2</td>
<td>+20</td>
</tr>
<tr>
<td>Waiting (sec)</td>
<td>12.3</td>
<td>14.6</td>
<td>+19</td>
</tr>
<tr>
<td>Speed (km/hr)</td>
<td>24.5</td>
<td>20.8</td>
<td>-15</td>
</tr>
<tr>
<td><strong>Edge 2</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Travel time (sec)</td>
<td>13.2</td>
<td>14.8</td>
<td>+12</td>
</tr>
<tr>
<td>Occupancy (%)</td>
<td>35.6</td>
<td>42.7</td>
<td>+20</td>
</tr>
<tr>
<td>Waiting (sec)</td>
<td>7.8</td>
<td>8.2</td>
<td>+5</td>
</tr>
<tr>
<td>Speed (km/hr)</td>
<td>35.8</td>
<td>33.2</td>
<td>-7</td>
</tr>
<tr>
<td><strong>Edge 3</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Travel time (sec)</td>
<td>14.2</td>
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</tr>
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<td>Occupancy (%)</td>
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<td>0</td>
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<tr>
<td>Waiting (sec)</td>
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<td>Speed (km/hr)</td>
<td>37.0</td>
<td>35.8</td>
<td>-3</td>
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<td><strong>Edge 4</strong></td>
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<td>Travel time (sec)</td>
<td>17.0</td>
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<td>+11</td>
</tr>
<tr>
<td>Waiting (sec)</td>
<td>13.5</td>
<td>14.2</td>
<td>+5</td>
</tr>
<tr>
<td>Speed (km/hr)</td>
<td>30.2</td>
<td>29.6</td>
<td>-5</td>
</tr>
<tr>
<td><strong>Edge 5</strong></td>
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<td></td>
</tr>
<tr>
<td>Travel time (sec)</td>
<td>10.1</td>
<td>11.1</td>
<td>+10</td>
</tr>
<tr>
<td>Occupancy (%)</td>
<td>48.3</td>
<td>53.1</td>
<td>+10</td>
</tr>
<tr>
<td>Waiting (sec)</td>
<td>10.5</td>
<td>11.2</td>
<td>+7</td>
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<tr>
<td>Speed (km/hr)</td>
<td>39.2</td>
<td>37.5</td>
<td>-4</td>
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<tr>
<td><strong>Edge 6</strong></td>
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<tr>
<td>Travel time (sec)</td>
<td>12.2</td>
<td>12.9</td>
<td>+6</td>
</tr>
<tr>
<td>Occupancy (%)</td>
<td>50.1</td>
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<td>+9</td>
</tr>
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<td>Edge 7</td>
<td>Travel time (sec)</td>
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<tr>
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</tr>
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<td></td>
<td>Speed (km/hr)</td>
<td>48.2</td>
<td>45.0</td>
</tr>
<tr>
<td>Edge 8</td>
<td>Travel time (sec)</td>
<td>9.9</td>
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<td>Occupancy (%)</td>
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<tr>
<td></td>
<td>Waiting (sec)</td>
<td>14.0</td>
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<td></td>
<td>Speed (km/hr)</td>
<td>30.2</td>
<td>25.6</td>
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<td>Occupancy (%)</td>
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<td>Edge 12</td>
<td>Travel time (sec)</td>
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<td>Speed (km/hr)</td>
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<td>45.0</td>
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<td></td>
<td>Waiting (sec)</td>
<td>12.5</td>
<td>14.9</td>
</tr>
<tr>
<td></td>
<td>Speed (km/hr)</td>
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<tr>
<td></td>
<td>Speed (km/hr)</td>
<td>37.0</td>
<td>36.8</td>
</tr>
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</table>

From Table 4.5, it can be deduced that active prioritization do have effect on the edges of the network but only minimal. For all of the edges considered the maximum increase in the general traffic travel time, occupancy and waiting time at any intersection were 16%, 20%, 19% and 15% respectively and a maximum of 15% reduction in the speed the vehicle would need to travel to cross over any of the intersection considered.

This result suggests that if the active prioritization process was well deployed, the benefits can make up for the little defect it has on the general traffic.

**4.9 PRIORITIZATION OF SIGNALS DISCUSSION.**

Prioritization at signalized intersection will increase bus reliability, reduce delay at intersections and consequently the bus travel time. However, it should be noted that the effectiveness of prioritization also depends on other factors such as the physical features, position and peculiarities of the bus corridor and lanes. When the Reavaya bus corridor features was compared with the other BRT system in the world, the following are some differences.

**4.9.1 BUS CORRIDOR POSITION.**

The Reavaya corridor runs at the center of the general traffic as seen in figure 4.20 causing huge interference from the general traffic and vice-versa though it runs on a bus only route. A look at some BRT with active prioritization along corridors reveals that the corridors were actually separated from the general traffic as seen in figure 4.19. The separation reduces the effect of left
or right turns on the bus corridor and also reduces the “extra-delay” effect that actively prioritizing a bus-lane has on the general traffic.

![Diagram of bus way and general traffic](image)

**Figure 4.27 The Orange-Line. Bus way completely separated from the general traffic**

It should however be noted that before a BRT system can successfully have its corridor completely separated from the general traffic, the system must have been planned into the city when the city itself was being planned. There should have been a ready-made plan for a BRT system and not just an integration and “coupling” into the existing transport or traffic network.

![Bus way at the center of the general traffic](image)

**Figure 4.28 Bus way at the center of the general traffic**
4.9.2 NUMBER OF SIGNALIZED INTERSECTION PER KILOMETER.

Obviously a separated corridor from the general traffic would have a lower count of signalized intersection per kilometer which makes the use of active prioritization cheaper (since less intersections mean less installations of detectors and transmitters), more effective and less impact on the general traffic. The Reavaya corridor studied has approximately 2 signalized intersection for every 1 km. This is a little high when compared with BRT system (Los Angeles Orange line and the Beijing Southern Axis BRT line) [107][108] with active prioritization technique which has as low as approximately 2 signalized intersection for every 1.5 km.

4.10 PROPOSED PRIORITIZATION TECHNIQUE.

After a good study (involving simulations) of the nature of the Reavaya corridor. It was concluded that an active priority technique would be needed (despite the two corridor weakness stated in section 4.9.1 and 4.9.2) considering the enormous benefit it yields in terms of travelling time for the buses and reduction in the release of pollutants.

4.11 SUMMARY.

An analysis of the travel time elements of the Reavaya BRT was discussed. The travel time elements were further analyzed by period of the day and the direction of travel. The result of the delay at signalized intersections as measured by the proposed model was then compared with the field measurement values and also with the Canadian model. The results from the modelling and simulation processes were then discussed. The chapter concludes with a discussion on the prioritization technique that is suitable for the Reavaya corridor.
CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1. INTRODUCTION

A thorough work on the delay experienced at signalized intersection along the bus only route by the BRT buses of the city of Johannesburg have been reported in this project. A model was proposed in other to measure the delay experienced at signalized intersections. The model included the delay experienced as a result of deceleration of bus and its subsequent acceleration to its travel velocity. Also, simulations of a section of the BRT corridor were executed in other to study the effect of active prioritization of buses at signalized intersections and thus comparing the results with when the intersections were un-prioritized. The following are the observations and the conclusion drawn from the study.

5.2. CONCLUSION.

The following are the conclusions.

1. Active prioritization of signals at signalized intersections reduced the waiting time of buses at intersections and has a minimum impact on the flow of general traffic along the bus corridor.

2. For all of the edges considered the maximum increase in the general traffic travel time, occupancy and waiting time at any intersection were 16%, 20%, 19% and 15% respectively and a maximum of 15% reduction in the speed the vehicle would need to travel to cross over any of the intersection considered.

3. An active priority system at bus-only route signalized intersection is very important in improving not just the bus travel times but also reducing to a great deal emissions of pollutant and fuel consumption rate. As 68% decrease in waiting time (at signalized intersections), 13% decrease in CO\textsubscript{2}, 17% decrease in CO, 12% decrease in HC, 15% decrease in NOx and 15% decrease in PMx were recorded.

4. The value of delay as a result of deceleration and acceleration of the bus is huge and an accurate delay measurement cannot be estimated while neglecting the acceleration and deceleration values.

5. The mathematical model proposed measured more accurately the overall delay experienced by a bus at a signalized intersection when compared to other delay models and the DT (delay time) component of the proposed model was very close to the on-site field measurement value (with as little as 1% difference at some intersections).
6. The number of legs of an intersection has a direct relationship to the delay experienced at that intersection for both peak and off-peak periods and the relationship is much more pronounced during off-peak periods.

7. During off-peak periods, the effect of skew on average delay at intersections with same number of legs is minimal but the effect can be noticed at peak periods. An increase of about 3.8% was recorded at three-leg skewed intersections.

5.3 RECOMMENDATION

The following is a recommendation:

- As much as possible, the BRT corridors should be actively prioritized at signalized intersections as the benefit of lower travel time has the tendency to drag a lot of commuters to the system.
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APPENDIX A.

- **PROPOSED MODEL AND CANADIAN MODEL DELAY CALCULATOR.**

| A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S | T |
|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 'This program helps to calculate the Delay Experienced by Buses on a Bus Only Route Intersection
| To start click on the START button below
| START
| CLEAR
| Harmony street/mall intersection delay
| t | t | μ | v | u | C | g | h | j | PWR |
| 0.2 | 0 | 0.750 | 42.672 | 0 | 99 | 17 | 30 | 103 | 1.36 |
| SST | 3.30132 |
| DT | 44.7755 |
| AT | 8.95342 |
| TOTAL DELAY | 57.028 sec. |

The symbols as seen in the table have the following meanings:
- τ: perception reaction time of bus driver (sec)
- μ: coefficient of static friction
- τ: free flow velocity of bus along corridor (km/hr)
- u: initial velocity, usually taken to be zero m/s
- C: Cycle length of traffic signal (sec)
- g: allocated green time of traffic signal (sec)
- h: bus only route headway
- j: gradient of the bus only route (+ for a rise - for a fall)
- τ: capacity of the bus only route
- PWR: Power to weight ratio of bus
- SST = stop sight time (sec)
- DT = Delay Time (sec)
- AT = Acceleration Time (sec)

**NOTE:** PWR for Articulated is 1.28 and for Regular Bus is 1.58

### TABLE OF INTERSECTION AGAINST DELAY

<table>
<thead>
<tr>
<th>NAME OF INTERSECTION</th>
<th>DELAY AS CALC'D</th>
<th>DT</th>
<th>AT</th>
<th>CANADIAN FIELD Measurement delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harmony street/mall/road</td>
<td>57.028</td>
<td>3.30132</td>
<td>44.7755</td>
<td>8.95342</td>
</tr>
</tbody>
</table>

Model works best when the headway of bus only route is adhered to

- **TRAFFIC INTERSECTION CAPACITY CALCULATOR.**
## Traffic Intersection Capacity Calculator [109]

- **A COPY OF THE ON-SITE FIELD MEASUREMENT CHAT.**
APPENDIX B

BRT IN AFRICA.

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ABSTRACT

In this paper, a comprehensive literature of bus rapid transit (BRT) development in Africa was discussed. The paper looks into the implementation and operation of BRT in Africa as well as its success and limitations. The paper discusses the practice of BRT in Africa while comparing it with those of other continents. The first BRT in Africa started operation in March 2008 and since then, Africa has only four running BRT systems in two countries out of the 204 running BRT systems in the world (which are “Lagos BRT lite” in Lagos, Nigeria; “Rea Vaya” in Johannesburg, South Africa; “MyCiTi” in Cape Town, South Africa and “A Re Yeng” in Tshwane, South Africa) as at the time of writing this paper. The paper concludes by motivating for new BRT systems in African cities and suggesting recommendations that fit into the similar economic challenges experienced in Africa.
KEY WORDS

Bus Rapid Transit; Africa

INTRODUCTION

Urbanization is a phenomenon with effects that cannot be overlooked. It has been described as the movement of people from the rural areas to the urban areas. Africa has been named to have the highest urban growth rate, with an annual average of about 7% and a growth rate of about 10% (Derek, 1974). At present about 325 million people live in the urban settlement in the sub Saharan Africa and UN estimates that the number would be three times in the next few decades reaching up to 1 billion by 2050 (LSE, 2013). It is obvious that with this urbanization come traffic congestion and transportation challenges as observed in major cities in Africa. Therefore a good sustainable transportation plan is of necessity.

A bus rapid transit has been identified as a transport system that runs on bus while imitating the traditional high capacity and performance of the urban rail system at a much lower cost and implementation. The Institute for Transportation and Development Policy (ITDP) defined BRT to be “a high quality bus based transit system that delivers fast, comfortable and cost effective urban mobility through the provision of segregated right of way infrastructure, rapid and frequent operations and excellence in market and customer service.” (Wright and Hook, 2007).

The rapid and geometric growth of BRT system around the world proves its relevance and contribution not only to public transit but to the economy especially in developing countries or transition economies. When evaluated in terms of environmental, social and economic advantages, BRT’s record gives a strong and compelling reasons for more cities to consider as a transit priority ( BRT successes in Ahmedabad, Guangzhou Johannesburg, and Bogota (to mention a few) proves that high end BRT service can be built at a low cost and short period of time. When compared with metro rail systems, studies revealed that metro rail systems can be ten times more expensive to build than a similar length of BRT (Suzuki et al., 2013). According to a study carried out by the Institute for Transportation and Development Policy (ITDP), BRT systems cost are typically in the range of US$ 500,000 per kilometer to US$ 15 million per kilometer while light rail transit (LRT) appears to be in the range of US$ 13 million to US$ 40 million per kilometer. Elevated light rail systems can range from US$ 30 million per kilometer to US$ 100 million per kilometer. The underground metro systems seem to range from US$ 45 million per kilometer to as high as US$ 320 million per kilometer (Wright, 2014).
Besides the cost advantage over other transit systems, BRT system can be built quickly in phases or segments and developed over time which affords some segments to be opened for commercial use while other segments are under construction. Though the reason for building a BRT system differs from one location to the other, (as pointed out by Cervero (1998) “...early BRT adopters built bus ways mainly because they were more affordable than light rails..”) but in the last few decades, bus rapid transit systems are built to complement the urban rail system or the preexisting prevailing mode of transit.

A look into the BRT systems by countries and regions reveal that Brazil (which is credited with the first BRT in the world) has 34 cities running the system, a pattern that has been followed by other South American countries making the region a giant in the system with a total of 67 cities running the transit in 13 countries. China has a similar story, boasting of about 37 corridors in 20 cities. Many other countries and regions that are taking advantage of the various advantages BRT offers in promoting public transportation and improving the congestion usually experienced especially in developing and growing cities.

This paper takes a study into the four existing BRT system and some other Bus services not fully implementing the Bus rapid transit features in Africa.

The paper is divided into three different sections. The first discussing the implementation, operation and limitation of the four running BRT systems in Africa. The second presents the global situation of BRT system with a spotlight on Africa. The paper afterward concludes with recommendations in implementing BRT systems for government and transportation stakeholders in Africa.

LAGOS BRT-LITE.

Lagos, a city in Nigeria with a population of about 21 million people (an estimate by the National Population Commission of Nigeria, 2014) making it the largest city by population in Africa. Lagos BRT-LITE began operating commercially on the 17th of March 2008 (Mobereola, 2009) making it the first BRT scheme in Africa. The word “LITE” was used to reflect the fact that the system is not a high end system, that is, it does not offer all the BRT standard services. As pointed out by Cervero (2013), BRT Lite may have limited technological applications and a more traditional means of collecting fare.
The Lagos BRT lite operates along a 22km stretch corridor that links the Lagos CBD to the extended mainland area of the city (Mobereola, 2009). The corridor has about 65% of its lane separated from the traffic, 20% exclusively for the buses and buses travel with the rest of the traffic for the last 15% of the corridor. The buses are painted light blue and deep blue which clearly distinguish it from other buses as it is the common practice with BRT systems. Fare collection is however not automated but is done just before boarding. The bus lanes are only for the buses and no commercial vehicle is allowed to use the lane even at peak hours (ITP/IBS, 2009).

According to Leadership Nigeria, (2015) the system moves about 180,000 commuters daily and is expected to move about 400,000 commuters when the ongoing expansion scheme has been concluded. The system moves about 10,000 commuters in peak hour one way, with a headway of about 30 seconds in peak hours and 45 seconds in off peak hours (Mobereola, 2009). Mobereola (2009) further revealed that the system transports over a quarter of all trips along its corridor even though the buses only accounts for 4% of all vehicles plying the route.

As pointed out by LAMATA (2013), the system has transported over 400 million passengers in the last five years. Other benefits of the system pointed out by the transport agency include; passengers enjoying average of 30% reduction in fares, 40% savings in journey time, 35% savings in average waiting time, direct employment to over 1,000 people and indirect employment to over 500,000 people.

The system has an operating cost of USD1.4 million per kilometer (which is arguably the lowest in the world) and an average speed of 20 km/hr.

**THE REA-VAYA.**

Rea-vaya meaning “we are going” is the name coined out for the bus rapid transit system in Johannesburg. Johannesburg is the largest city in South Africa with a land area of 1,645 square kilometer and a population of 4, 434, 827 as at 2011 (Statistics South Africa). The BRT system construction started in 2007 and operation started on 30th of August 2009 linking the city’s central business district and Braamfontein with Soweto. Allen (2013) documented that the first phase started with 25.5 km route that links Soweto with Ellis Park with five feeder services and two complementary services linked to the trunk using 143 buses.

Unlike the BRT Lite, the Rea vaya includes most of the services a standard BRT system offers making it a high-end system and the first full BRT system in Africa with an estimated operating
cost of USD 8-10 million per km it achieves an average running speed of 28km/hr (Brader, 2011). Rea-vaya system includes attractive and functional closed stations, pre-paid boarding, and level boarding for easy access into and out of the buses creating easy boarding for the physically challenged. Other operational characteristics of the bus include; 60 foot, low emissions articulated buses that runs through the trunk; 48 enclosed stations with controlled entry and exit; the buses have multiple doors for quick exit and entrance, headway of about 3 minutes at peak periods and 20 minutes at off peak periods, stations have passing lanes to facilitate movement of express busses.

Rea vaya was rated silver by the Institute of Transportation Development Policy (ITDP) in the year 2000 which reflects its quality of service and its ability to deliver a world class transit experience.

At present the Rea-vaya runs on 59km of trunk routes with a total of 277 buses, runs on three trunk routes, six complementary routes and twelve feeder routes, 488 jobs have been created at the stations and with the start of phase 1C (under construction), 1000 more jobs will be created at stations for ambassadors, cashiers, marshals, cleaning and security personnel. The phase 1C of the project which is expected to be completed by 2017 will include 30.5km of extensive walking and cycling paths and also create 5700 jobs during its construction.

To date, a total of about R3.7 billion has been spent on infrastructure and the estimated cost of phase 1C is R3- billion (source: www.reavaya.org.za)

**MyCiTi**

MyCiTi is the official name of the BRT system of the Cape Town city. Cape Town is a city in South Africa. The city of Cape Town has a population of 3, 740, 026 (Statistics South Africa), the second most populous city in South Africa, located in the province of Western Cape. A city once named the best place in the world to visit by the America New York Times (Cape Town magazine) would no doubt work towards having a world class transport system.

MyCiTi rolled out its first phase of BRT in May, 2011 though it had started service May 2010 shortly before the 2010 FIFA world cup competitions and was used to convey fans and supporters. Running a total of 36 routes and a daily ridership of 60,000 commuters (My CiTi monthly operations report, November 2015), the system cost a total of about USD 477 million (Urban African, 2015). The system boasts of 42 bus stations, about 600 bus stops and about 223 modern...
low-floor buses. The system like others make use of the prepaid ticketing system to access the buses. Cyclists have good opportunity to connect with the system by making use of the cycle paths that runs alongside with the bus route, this in return encourages the non-motorized mode of transit. To improve the services offered by the system, an on-board wifi system has also been made available in some MyCiTi buses which allows commuters to check their mails, browse the social media and also view some internet contents by giving them a daily data of 50mb. As revealed by MyCiTi News (10 June 2016), the system will kick off on the 13th June.

All these services have received commendations from commuters using the system some of which affirmed that the BRT system was the only reason they are making use of public transport system as they do not have to worry about where to park their cars.

A Re Yeng

A Re Yeng (meaning: Let’s go) is the name of the BRT system in the city of Tshwane, a city that covers a land area of 6,368 square km and a population of 2,921,488 (Statistics South Africa). The construction of the BRT started 11th July, 2012 and started operating on December 1, 2014. It runs from the central business district to Hatfield and also connecting with the mass rapid train system (named Gautrain) at Hatfield.

The system runs on 80 kilometer bus lines, 62 stations that are located at the central median of the road and about 340 low-floor buses (showme, 2016, Engineering News, 2016).

The system makes use of the closed ticketing system for access into the stations. A typical A Re Yeng station has an access ramp which has a maximum of 1.15 gradient to facilitate movement of mobility impaired people, kiosks where payment can be made and information about the bus acquired, gates that validates ticket at entrance and exit, multiple automated doors at both ends of the station to allow for faster entrance (and exit) into the bus, real time passenger information and staff facilities.

Its’ trunk service are made to operate on exclusively dedicated lanes while the feeder service that brings commuters to the trunk are to operate in the mixed traffic. The system has a daily ridership
of 4,600 passengers. By 2020 when the project has been fully completed, the daily ridership is estimated to be about 100,000 passengers. The system cost about USD 0.286 billion.

**TABLE 1: OVERVIEW OF THE FOUR BRT SYSTEMS BASED ON STANDARD BRT ELEMENTS.**

<table>
<thead>
<tr>
<th>Standard BRT Elements</th>
<th>Lagos BRT Lite</th>
<th>The Rea vaya</th>
<th>MyCiTi</th>
<th>A Re Yeng</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Running Way</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>● Length of separated Running way</td>
<td>About 14 Km</td>
<td>59km</td>
<td>About 55km</td>
<td>56km</td>
</tr>
<tr>
<td>● Method of Segregation from other Traffic</td>
<td>Raised median (Curb)</td>
<td>Concrete, Elevated pavements and barriers.</td>
<td>Elevated barriers</td>
<td>Elevated barriers</td>
</tr>
<tr>
<td>● Location of Bus Lanes</td>
<td>Median</td>
<td>Median</td>
<td>Median</td>
<td>Median</td>
</tr>
<tr>
<td><strong>Fare Collection</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>● Fare Payment Process</td>
<td>Off board payment</td>
<td>Off board payment</td>
<td>Off board payment</td>
<td>Off board payment</td>
</tr>
<tr>
<td>● Fare Payment Media</td>
<td>cash</td>
<td>Smart card</td>
<td>Smart card</td>
<td>Smart card</td>
</tr>
<tr>
<td><strong>Stations</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>● Number of Stations</td>
<td>Most stations are not enclosed and are more like</td>
<td>48 enclosed stations</td>
<td>42</td>
<td>62</td>
</tr>
<tr>
<td>Type of Platforms</td>
<td>Platforms not raised</td>
<td>Platforms raised for level boarding</td>
<td>Platforms raised for level boarding</td>
<td>Platform raised for level boarding</td>
</tr>
<tr>
<td>-------------------</td>
<td>----------------------</td>
<td>------------------------------------</td>
<td>------------------------------------</td>
<td>-----------------------------------</td>
</tr>
<tr>
<td>Vehicles</td>
<td>Conventional and standard bus</td>
<td>Conventional but articulated bus</td>
<td>Stylized articulated and low floored</td>
<td>Stylized articulated and low floored</td>
</tr>
<tr>
<td>Trunk Vehicle type</td>
<td>Diesel</td>
<td>Compressed Natural Gas</td>
<td>Diesel</td>
<td>Compressed Natural Gas</td>
</tr>
<tr>
<td>Type of fuel used</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intelligent</td>
<td>Not available</td>
<td>Available but not active (Next Bus arrival time available online)</td>
<td>Available but not active (Next Bus arrival time available online)</td>
<td>Not Available (Next Bus arrival time available online)</td>
</tr>
<tr>
<td>Transportation system</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Next Bus Arrival Signs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Precision Docking</td>
<td>Not available</td>
<td>Precision docking used</td>
<td>Precision docking used</td>
<td>Precision docking used</td>
</tr>
<tr>
<td>Transit Signal</td>
<td>Not Available</td>
<td>Not fully implemented</td>
<td>Not fully implemented</td>
<td>Not fully implemented</td>
</tr>
</tbody>
</table>
A REVIEW OF BRT STATISTICS AROUND THE WORLD.

The BRT system has been widely accepted as a cost effective mode of transport when compared with the urban rail and yet still giving the major benefits the urban rail offers. It growth globally over the past ten years is unprecedented. As at the time of this research, there are about 204 cities globally that make use of the system, running on a total of 5,333km (bus only route) and
transporting about 33,294,692 commuters daily (Source: BRTdata.org). As seen in figure 1, BRT is most popular in South America (its’ origin) being available in 67 cities.

![BRT distribution around the continents](source: BRTdata.org).

Table 1 shows BRT system development statistics across the globe and a greater percentage of the BRT system were built in the last 10 years revealing the sharp growth of public transport around the world. The first in China was implemented in 1999 at Kunming and was followed five years after by the one in Beijing. In 2010, Guangzhou BRT was also implemented as a high capacity system transporting more commuters than most of the available metro lines in China (TheCityFix, 2013). BRT in China has witnessed an exponential growth in the last few decades as seen in figure 2.

As at 2012, China had about 500km of BRT lines in busways and mixed traffic. Today china has over 20 cities running the BRT system transporting over 4,375,250 commuters daily over a stretch of 655 km bus only route (BRTdata, 2016).

Table 2 **BRT SYSTEM STATISTICS ACROSS THE GLOBE.**

<table>
<thead>
<tr>
<th>Regions</th>
<th>Passengers per day</th>
<th>Number of Cities</th>
<th>Length of bus only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Africa</td>
<td>13.7%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Asia</td>
<td>20.6%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Europe</td>
<td>32.8%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>South America</td>
<td>28.4%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>North America</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oceania</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Route (km)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>-----------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Africa</td>
<td>262,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Asia</td>
<td>9,293,372</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Europe</td>
<td>2,017,347</td>
<td></td>
<td></td>
</tr>
<tr>
<td>South America</td>
<td>20,274,549</td>
<td></td>
<td></td>
</tr>
<tr>
<td>North America</td>
<td>1,017,383</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oceania</td>
<td>430,041</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(Source: BRTdata.org)

From the statistics it is quite evident that Africa is yet to tap into the enormous benefit BRT system has to offer.

**FUTURE OPPORTUNITIES FOR BRT IN AFRICA.**

Africa’s population as at June 2016 was estimated by the United Nations to be 1,214,948,499, an equivalent of 16.14% of the total world population. It was also estimated that 39.8% of the African population (which equals 488,296,186) lives in the Urban. According to the UN World Urbanization prospects report (2010), it was reported that about 40 cities in Africa have a population of over 1million. Lagos has the highest population with about 8 million people. Analysis also proves that by 2050, the continent would have been twice its’ population and 80% of the growth would be in the Urban cities.

The result of this rapid growth rate and urbanization depends largely on what Africa’s political, economic and business authorities do next. Eyewitness news reports that if these authorities take the right steps, decisions and reforms, there will be innovation, employment and economic growth and if these authorities fail in these the result will be poverty, sluggish economic growth and instability.
A direct consequence of urbanization is more challenges in mobility. Transportation plays a major role in growing cities as it has direct impact on the population, economy, education, services etc. A knowledge of this is the major reason why developed and developing countries have invested so much into transportation as seen in the growth of BRT system around the world. A lot of research has shown that BRT system has been able to reduce travel times of commuters around the world by several days in a year. Report from World Resource Institute (2013) shows that commuters in Johannesburg have the ability to save over 9million eight hour work days from 2007 to 2026 just by shifting from other mode of transport to the use of BRT. Similar to this are commuters in Istanbul, Turkey that can save 28 days every year just by using the BRT. Other thorough studies of BRT in Mexico City, Mexico; Johannesburg, South Africa; Istanbul, Turkey; and Bogota, Columbia concludes that BRT offered benefits in the following ways (Gretchen Stevens, 2008):

- **Economic benefit** by reducing travel times, offering a much more reliable transport service, improved working conditions for commuters, increased economic productivity and increase in employment.
- **Environmental benefit** by reducing dangerous emissions from vehicles and reducing to a large decree noise pollution.
- **Social Benefits** by promoting a much more better access to the city, reducing accidents and injuries as a result of overcrowded traffic and instilling into the commuters a sense of civic pride and belonging.
- **Urban Reform** by promoting and enhancing densification along major routes.
CONCLUSION AND RECOMMENDATION

The global impact of BRT system on public transit is reflected in its rapid growth. In this paper, focus was on the four running BRT system in Africa and the development of the system in Africa was compared with that of the other continents with similar challenges (Asia and South America). It was however observed that Africa is yet to tap into the enormous benefits the system has to offer. It was also observed that though Africa is yet to tap into BRT benefits, there are opportunities for Africa to do so with its growing population and rapid urbanization coupled with the privilege of learning from successes and failures of BRT systems in countries of similar economic challenges and growth.

The following are good practice approaches for delivering a good BRT system as revealed by successful and failed BRT in the world.

1. A holistic, thorough and detailed planning process which focuses on how the BRT would meet the commuter’s transportation need and their expectation. The planning must also include how the BRT corridors can be integrated into existing mode of transports (such as the metro rail, bus routes and cycling routes) not just as a standalone transport system.

2. A phase by phase implementation of the project with surveys and commuters feedback undertaken before, during and after the execution of each phase of the project. This helped
in preventing mistakes or inadequacies of the previous phase from being repeated in the next phases.

3. Stakeholders in the transport industries must be actively carried along especially the pre-existing taxi or mini buses industry which normally perceive their sustainability and livelihood to be in danger by the introduction of the BRT system. A good practice is to enlighten this industry on the benefits of the BRT system and include them early in the planning by giving them roles and opportunities in the BRT system being planned.

4. A good and strong political leadership. As this may not seem to be very important, a poor political leadership has led to failure of some BRT systems around the world.

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