METHODOLOGY TO DEVELOP A FEEDER BUS NETWORK FOR A LIGHT RAIL TRANSIT SYSTEM:

A Case Study for Fort- Malabe Line

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188101A

Degree of Master of Science

Department of Civil Engineering

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DECLARATION

I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

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Name of the supervisor: G.L.D.I. De Silva

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ABSTRACT

The world is reaching towards the sustainable transportation and the public transport sector especially requires a better focus and attention. Public transport network can be better distinguished as mass transit systems and feeder systems. Mass transit systems strengthens the transport network as backbone transport systems. However, it does not enable the connection between the origins such as the residence or the work place and the mass transit access points. This connection which is a vital component is enabled by the feeder modes. There can be several variations in feeder modes. Especially it can be recognized as private feeders and public feeders. Without a proper feeder network, the maximum potential of a mass transit network may not be achieved.

In this research, the focus is on the Light-Railway transit which is the most recent mass transit system that is being introduced to Sri Lanka. As the first step of introducing the light railway system to Sri Lanka, Fort-Malabe LRT was planned to be implemented. Even though the plans by the Government have changed, in this research, Fort- Malabe LRT line is taken as the case study in order to carry out the objectives. The feeder modes that are supplying to the LRT line were recognized as private vehicle drop offs, para-transit modes and short length public transit modes.

In order to get an uninterrupted connection between the origin and the mass transit access station, the development of feeder network that will be serving the mass transit has to be parallel with the development of the mass transit system. However, the LRT orientated development also has to be limited by the necessity. In order to get a realistic estimation on the development required area, the spatial extent of access areas by different access modes have to be identified.

The spatial area where potential transit users will origin their trip to use the mass transit can be identified as the catchment area. Catchments for different feeder modes may vary depending on the distance that users prefer to travel by that particular feeder mode. Catchment areas for multiple access modes were recognized using the survey data which were available from a previously carried out survey.

In identifying catchment distances for different feeders, two methods were followed. First method was to consider each station and identify the preferred travel

distances by a certain feeder mode to reach that station and thereby calculating a weighted average catchment distance for the chosen station for that particular mode. To calculate a catchment distance value which justifiably represents all the stations for a certain feeder mode, an average value was calculated.

Second method that was carried out was to consider the LRT route aligned corridor and identify catchment distances for each feeder mode which will represent the Fort-Malabe corridor rather than each station. The individuality of stations was not considered. To identify the catchment distance for a specific feeder mode, all data records of trips originating from a catchment to reach any station by that mode were taken in to account. The frequency of access distances occurring was the basis of the second method. Therefore, the frequency of a certain access distances occurring was identified and thereby the cumulative frequency of access distances was taken. When the accumulation of frequency reached 85th percent, the catchment distance at the point was taken as the catchment distance for that certain feeder.

In order to determine the geographical buffer area, two approaches were identified that can be utilized. First was the circular buffer approach which takes the Euclidean catchment distance from the LRT station locations. Aspects such as the geographical barriers and the non-availability of road network were not considered in this case. The other approach was to take the service area. In this approach the travel distance of the catchment is determined via the road network. Considering the pros and cons of two approaches and the accuracy of the results by each approach, service area approach was appointed to be used. Thereby the catchment areas were configured for the access modes. The catchment areas for each feeder type were visualized with the use of Geographical Information Systems (GIS).

In the case of the bus feeders, it was observed that the catchment area also depends on the bus route path layout. Areas which are parts of the bus catchment but does not get supplied with the bus network, can be identified separately. In this scenario, Conveyal analysis was used to identify the bus catchment which is limited by the availability of bus routes in the catchment which is bounded by the catchment distance. As per the first objective of the research, catchment area for multiple feeder modes were identified as above.

Further, it was observed, for a particular feeder mode, that there are certain areas that are not supplied by the respective feeder mode inside the catchment area which is due to the lack of road network or due to physical barriers such as water bodies. For each feeder mode type, the possibility of expanding the catchment area coverage was investigated. For walking and cycling mode it was identified that foot path implementation can expand the catchment coverage significantly. However, for the private vehicle and taxi modes, it was identified that the furthering the coverage is not practical. In the case of bus feeder, a detailed analysis on maximizing the coverage of catchment area was carried out.

For this step, two bus network design methods were identified. First method was to modify the existing bus network of regular routes in the catchment to accommodate the demand for feeder and include separate feeder routes for demand that is not covered by the regular routes.

The second design method was to implement a feeder network for the catchment, aiming to supply the full demand for the bus feeder, which will operate independent of the regular routes. In fact, aim is to dissolve the existing regular network and back the public transit completely by feeder routes and the backbone LRT transit.

The two design methods were thoroughly analyzed regarding the coverage by each and the practicality of implementation and the most suitable methods was selected. Thereby, an optimization procedure was carried out to optimize the designed bus network by methods such as route merging, breaking etc. From this procedure, an optimum route network can be identified.

Overall, this thesis contains a methodology for feeder bus network design for a LRT in Sri Lankan context, which takes the Fort- Malabe corridor as the case study sample.

DEDICATION

To My Loving Parents and Husband,

Who Kept Me Going on Through Highs and Lows

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14.11.2021

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1 INTRODUCTION

1.1 Transportation Structure of Sri Lanka

Transportation structure of Sri Lanka heavily rely on road network transportation. The public transportation utilizing the road network is also operating under the congested condition most times which is specially seen in Western Province. In morning and evening peak hours, the travel speeds can be observed to be significantly low. Therefore, the road structure users, through private and public modes are facing this situation alike.

The other public transport mode available in Sri Lanka is railway. However, the access points and the railway lines are limited, therefore does not enable the best accessibility conditions. Even if railway allows to travel without congestion. However, railway service presently is highly unreliable.

Light Railway Transit is an urban rail transit form, which is now commonly used in world even though Sri Lanka is yet to operate one. It is vastly advantageous because it enables a higher number of urban passengers to travel comfortably and in lesser travel times through congested urban cities. It is also proven to be economical due to the lower operating costs for passengers and environmentally less harmful due to lower noise levels.

Throughout the world, multiple cities which have adapted the light railway transit successfully can be observed. As by December 2018, LRT systems were available in 389 cities worldwide. The urban rail is a major aspect, especially in South Asia and it is expected to continue to be so. Sri Lanka is no exception. In 2017, even with a modal share of 3.9%, Sri Lanka Railways, catered to more than 136.6 million passengers (National Transport Commission, 2018).

In Sri Lanka, the major economic capital, Colombo, and its access corridors can be observed to be highly congested at peak hours. The seven corridors are as shown in Figure 1.

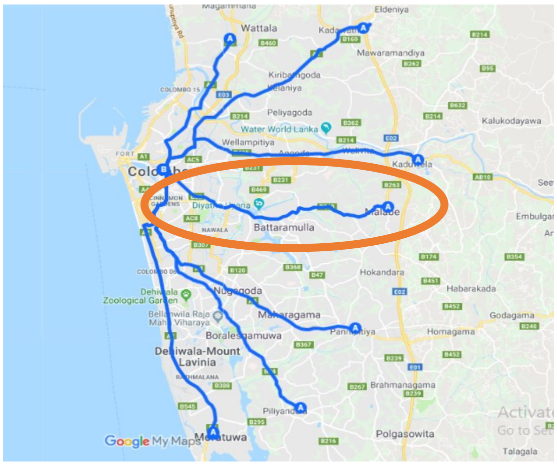


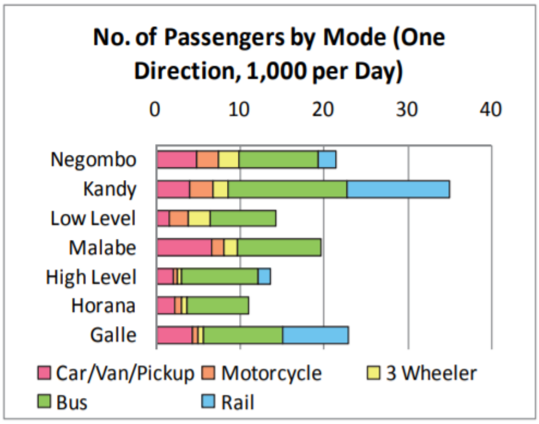
Figure 1: 7 Corridors to Access Colombo

Table 1, contains the recorded peak hour traffic and the passenger volumes and Figure 2 shows the number of passengers by mode in a direction per day in those corridors in 2018.

Table 1: Access Corridor Peak Hour Traffic

Corridor Name	Peak Hour Road Traffic (2014)	Peak Hour Passenger Volume (2014)
Malabe Corridor	5100 pcu/hr	23,500 pax/hr
Galle Road Corridor	2900 pcu/hr	22,900 pax/hr
Kandy Road Corridor	4400 pcu/hr	37,200 pax/hr
Negombo Corridor	4000 pcu/hr	33,800 pax/hr
High Level Road Corridor	2000 pcu/hr	15,100 pax/hr
Horana Corridor	2200 pcu/hr	11,100 pax/hr
Low Level Corridor	2900 pcu/hr	14,300 pax/hr

Source: Urban Transport System Development Project for Colombo Metropolitan Region and Suburbs: Technical Report 6: Urban Transport Master Plan (Agency, 2014)



Source: CoMTrans Screen Line Survey 2013

Source: Urban Transport System Development Project for Colombo Metropolitan Region and Suburbs: Technical Report 6: Urban Transport Master Plan (Agency, 2014)

Figure 2: Passenger Volume by Mode for Seven Corridors

Table 2 contains the presently available public transit modes in those corridors and the improvements proposed by Urban Transport System Development Project for Colombo Metropolitan Region and Suburbs in the technical report (Agency, 2014).

Table 2: Present Transit Systems and Proposed Transit Systems in CoMTrans study

Corridor Name	Present Transit modes	Proposed transit modes in CoMTrans study (2014)
Malabe Corridor	Only bus transit	Monorail from Fort – Malabe
Galle Road Corridor	Bus and Railway	Modernized railway, BRT
Kandy Road Corridor	Bus and Railway	Modernized railway, BRT
Negombo Corridor	Bus and Railway	Modernized railway, Bus priority
High Level Road Corridor	Bus and Railway	Monorail
Horana Corridor	Only bus transit	Bus priority
Low Level Corridor	Only bus transit	Bus priority

Source: Urban Transport System Development Project for Colombo Metropolitan Region and Suburbs: Technical Report 6: Urban Transport Master Plan (Agency, 2014)

When considering the new proposals for transit lines, conditions in Table 3 were taken into consideration.

Following the proposals in CoMTrans study, the proposal of implementing Monorails was later changed for Light rails after some considerations. Therefore, Sri Lanka, going a step further in urban railway transportation, the light railway transit line concept was brought to light as the newest transit mode system. As the initiation step, in March 2018, the Cabinet of Sri Lanka, approved construction of a Light Railway Transit (LRT) line from Malabe to Fort after the completion of the feasibility study. This was proposed to be the first LRT line in Sri Lanka.

Table 3: Transit System Characteristics

System	Bus Priority System	BRT	AGT	Monorail	LRT	MRT - Elevated	MRT - Underground
Capacity*	-10k	3-13k	4-20k	7-30k	7-30k	18-60k	18-60k
Scheduled Speed	10-20 km/h	15-25 km/h	20-30 km/h	20-40 km/h	20-40 km/h	30-40 km/h	30-40 km/h
Land Acquisition	no acquisition	along roads	only stations	only stations	station & some roads	station & curve sections	station exit only
Stop Spacing	0.3 – 1 km	0.5 – 1 km	0.5 – 1 km	0.5 – 1 km	0.3 – 1 km	1.5 – 2 km	1.5 – 2 km
Initial Cost	USD ~1 M/km	USD 2 M/km	USD 30-60 M/km	USD 30-60 M/km	USD 35-60 M/km	USD 45-60 M/km	USD 90-100 M/km
O&M Cost	N/A	USD 1.3 / car-km $0.03 per pax.	USD 2.0 / car-km $0.04 per pax.	USD 2.5 / car-km $0.03 per pax.	USD 4.0 / car-km $0.04 per pax.	USD 5.0 / car-km $0.03 per pax.	USD 5.0 / car-km $0.03 per pax.
Daylight Interference	Not at all	Not at all	Pier & Slab	Pier & Beam	Pier & Slab	Pier & Slab	Not at all
Aesthetic Concern	No Concern	Station only	Pier & Slab	Pier & Beam	Pier & Slab		Not at all
Noise	Rubber Tyre & Engine	Rubber Tyre & Engine	Rubber Tyre	Rubber Tyre	Rail & Tyre	Steel Rail & Tyre	No noise to ground level

Note: * Capacities are in the number of passengers per hour, per direction. 1k means 1,000.

Source: Urban Transport System Development Project for Colombo Metropolitan Region and Suburbs: Technical Report 6: Urban Transport Master Plan (Agency, 2014)

1.2 Light Rail Transit

Light rail transit or the LRT is a transit of mid-sized capacity which is electrified and has an exclusive right-of-way. For Colombo, in order to mitigate the congestion, several LRT lines were proposed by taking the conditions of the corridor into consideration.

Most of the corridor in consideration has a road network which is at the capacity at present and due to the dense development along the corridor highway, proposition of widening the road to add more lanes and improving capacity is not practical. Any new transit line requiring a mass land acquisition is not feasible due to lack of vacant land and due to the high land value. Therefore, the possibility of a transit line operating on an elevated platform was considered.

In this case a LRT network was identified to be the best suited due to several reasons such as capacity being in mid-range, service quality, speed, frequency, the land use being limited, technical prevalence, being able to operate on ground and on an elevated structure both and thereby the ability to reduce cost, rail road switching being a simple system, having the ability to expand the network by crossings etc.

Currently all regions in the world utilizes LRTs. Countries such as China, Japan, Hong Kong are operating the LRTs with high capacities. Hong Kong in 2015, which has the highest passenger turnover transited nearly 5 million passengers per annum per 1km of LRT (International Association of Public Transport, 2015) (Transport, 2015). From 2000-2015, 78 cities have introduced LRT systems to their public transport sectors.

1.3 Feeder Modes in Sri Lanka

Feeder modes are the access and egress modes, that enables the mass transit users to reach the mass transit stations from their origins in access trips and to reach the destination from the mass transit station in the egress trip.

In Sri Lanka, the available mass transits are bus modes and the railways. The feeder modes used to fulfill the access and egress trips observed in Sri Lanka are walking and cycling, Private vehicles, Para-transit and public transit modes.

1.4 Fort – Malabe corridor

Out of the seven transport corridors, connecting to Colombo, Fort-Malabe corridor is of the least travel speeds and the highest traffic volumes according to the Urban Transport Master plan. At the peak hour traffic speed drops down to 14km/h and at peak hour, bus load factor reaches 138% according to the 2014 report (Agency, 2014).

However, this corridor is only supplemented with a bus network as the available public transit option. The option of a railway line is not available to the passengers using this corridor unlike in other corridors such as Kandy and Galle corridors.

Also, as seen in Figure 2, Malabe corridor has the highest modal share of private cars. And as shown in Figure 3, only 35% of passengers are travelling using private vehicles even though the modal share of private vehicles account for 51% of the vehicles. On the other hand, 50% of the passengers travel by bus mode, even if the modal share of buses is only 4%.

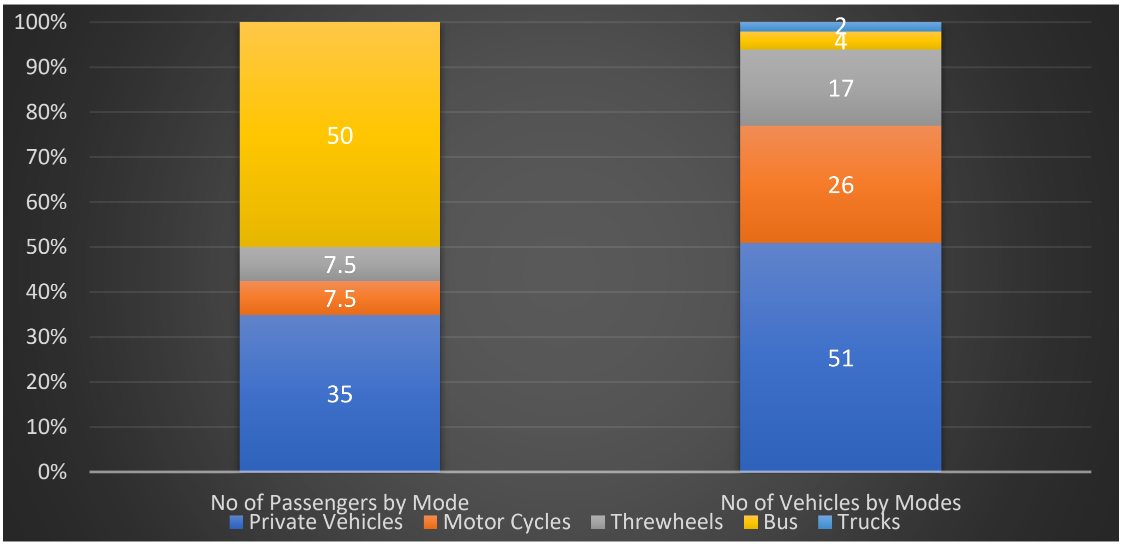


Figure 3: Mode Share of Fort-Malabe Corridor

Source: Urban Transport System Development Project for Colombo Metropolitan Region and Suburbs: Technical Report 6: Urban Transport Master Plan (Agency, 2014)

However, the high number of private vehicle usage may be due to the weakness of the public transport as the corridor lacks a railway network. The road section throughout the corridor is narrow and high-rise building are built along the corridor. Due to the recent relocation of many Government buildings to the Battaramulla area, which is a major city in the corridor, the employment congestion has risen exponentially (JICA, 2018) (Japan International Cooperation Agency, 2018). Therefore, an improved public transportation is a timely need. To supply the demand, a new LRT line was proposed.

1.5 Fort – Malabe LRT line

In 2013, an elevated Light Railway line of 15.3 km in length, which would operate mainly on center median of the existing roads was proposed to supply to the future demand occurring in this corridor. It was expected to be operational by the year 2024 and it was expected to ease the congestion along the highly congested Malabe Colombo corridor. This proposed LRT system was expected to carry approximately 360,000 and 500,000 passengers per day by years 2025 and 2035 respectively. The passengers were to have access to the LRT system through 15 proposed stations as shown in Figure 4.

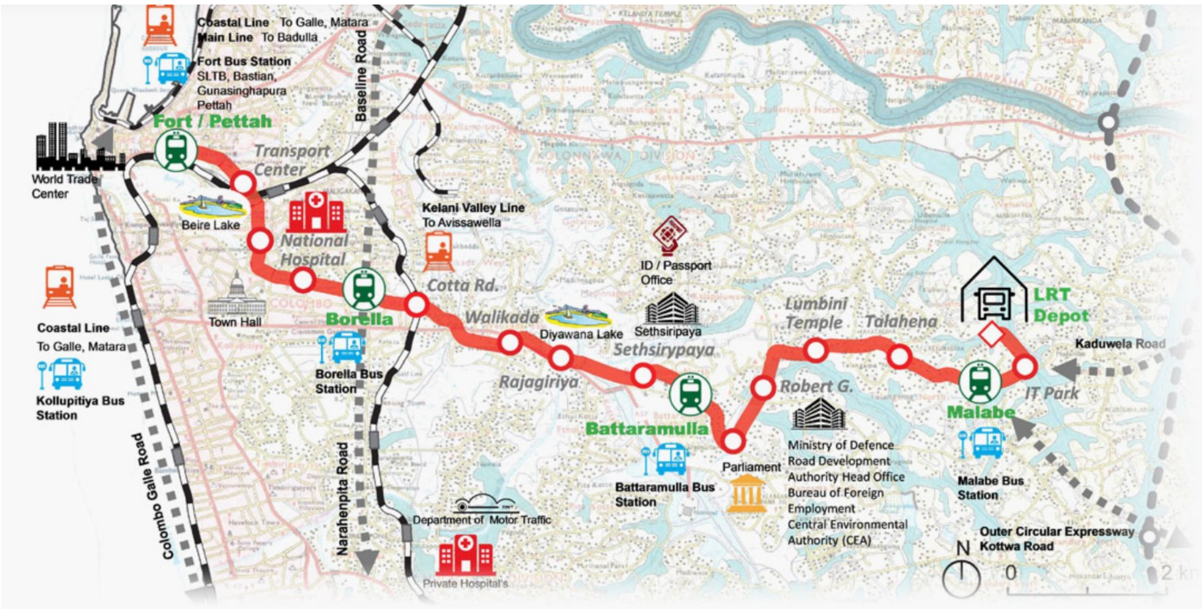


Figure 4: Proposed LRT Stations

Source: Urban Transport System Development Project for Colombo Metropolitan Region and Suburbs: Technical Report 6: Urban Transport Master Plan (Agency, 2014)

- Fort
- Transport Centre (Maradana)
- St Joseph's College
- National Hospital
- Borella
- Cotta Road
- Welikada
- Rajagiriya
- Sethsiripaya
- Battaramulla
- Robert Gunawardena Mw
- Lumbini Temple
- Talahena
- Malabe
- IT Park

1.5.1 Existing Bus Network

Currently the corridor and the surrounding catchment for this corridor consists of a bus network that operates mostly on primary road links. The bus stops that were identified in the Fort – Malabe corridor is shown in Figure 5.

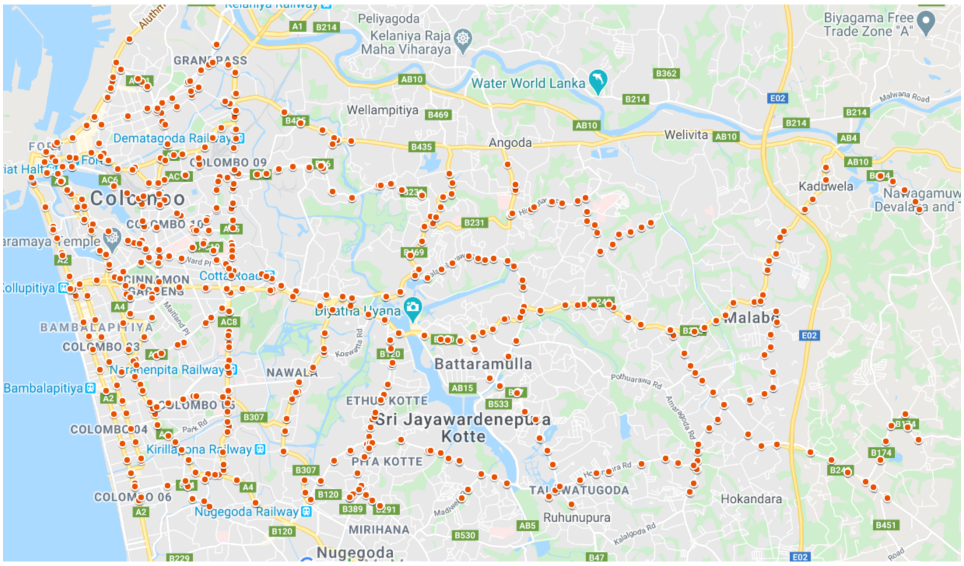


Figure 5: Bus Stops in Fort - Malabe Corridor

The bus routes that are running in the LRT corridor currently are majorly parallel to the proposed LRT line. Routes are more competitive rather than complimentary for the LRT line which is detrimental for both modes. While LRT is more efficient in connecting longer distances, the buses play a pivotal role of collecting the passengers and reaching to more residential communities thereby constructing a feeder network.

1.6 Scope of study

Light Railway Transit is the modern solution for the urban traffic congestion accepted worldwide. Most South Asian countries which are similar to Sri Lanka has successfully operating LRT lines. For Sri Lanka as well, LRTs are proposed at several major corridors. Therefore, this study concentrates on the Light railway Transit implementation in Sri Lankan context.

For the operation of a backbone mass transit to be in optimum condition, the connections made available by feeder modes are

Fort-Malabe LRT is the first Light Railway that was proposed to be implemented in Sri Lanka and the experiences of using the LRT as a transit mode and using feeder modes to access it is yet to be experienced. However, JICA, (2018) (Japan International Cooperation Agency, 2014) identifies the demand for the LRT line and it is reasonable to assume that feeders are required by the passengers to reach the transit.

Feeders can be of a variation and this research analyzes the catchments of different feeder modes available in the area. Taking the public transport modes that will be used as feeders as a special case, which in this case the buses, further analysis is carried out in the research.

In Sri Lanka the usual scenario is the bus to be the transit mode rather than the feeder mode. There are several methodologies identified in literature for the purpose of developing bus networks in Sri Lanka. However, as a such network of LRT being the transit and buses being its feeders has not been exercised in Sri Lanka before, focusing on identifying a methodology to design such a feeder bus network is a timely feat and is being carried out in this research.

1.7 Objectives of the study

The objectives of the research are as follows.

- Identifying the catchment areas by different access modes identified to be utilized as feeders, for the proposed Fort-Malabe LRT line
- Developing a methodology to identify an optimum feeder system for railway
- Appling the methodology to identify an optimum feeder system for proposed Fort-Malabe LRT

1.8 Arrangement of dissertation

Chapter one contains the introduction, which describes the background of the study, including the current transit network and the current operating feeder mode concepts, existing bus network, scope of the study, objectives and outcomes.

Chapter two is the literature review that was carried out for the study. The catchment area identification and design of feeder networks to address the catchment were reviewed upon.

Especially the bus feeder design was analyzed. Multiple studies that were carried out for bus network design and feeder network design were studied.

Third Chapter describes the research methodology that was carried out by steps.

Chapter four identifies the methodology to develop a feeder bus network for a Light Railway line in Sri Lanka in steps by referring the previous literature.

Chapter five illustrates the application of the methodology identified in Chapter 5 to Fort – Malabe corridor. The case study is carried out in steps mentioned in the Methodology of Chapter 4. This chapter discusses the data collection and the development of the data. It is concentrated on catchment distance calculation and catchment area identification. For each feeder mode, a catchment distance was calculated, and thereby, catchment areas were identified for each mode. And further this chapter identifies catchment areas. This chapter further investigates the bus feeder more specifically. The existing bus transit network and the effect from the existing network was identified in this chapter. Chapter 5 further is dedicated to discussing the bus network design methods. Under this chapter, two design methods are identified. The coverage by each method was identified. This chapter further analyzes this coverage by the two methods and finally selects the most suitable method considering multiple factors. Furthermore, this chapter focuses on the optimization of the bus network. Optimization is carried out by several methods such as route merging, breaking etc. Examples of each instance were shown.

Chapter six contains the conclusion and the recommendations for the research study, which briefs the outcomes of the study and the recommendations for the feeder modes in the LRT corridor.

2 Literature Review

2.1 Definitions

LRT – Light Railway Transit

Feeders – modes connecting the origins of the passengers with the backbone transit stations

Regular bus routes – bus routes that are aimed for connecting origins and destinations in the corridor rather than specified in connecting origins with transit stations. Existing bus routes are considered as the regular routes

2.2 Sustainable Transport

With the development of transport sector, it is inevitable that the congestion, accidents and air pollution will rise. However, development that is sustainable is the solution and the goal that is aimed to achieve in transportation as well as in other fields. Therefore, sustainable transport, which is defines as the "transport that satisfies the current transport and mobility needs without compromising the ability of future generation to meet these needs" (Black, 2010), is a key focus of new transport developments.

It is shown by the data that transport sector is a main contributor to the green-house gas emissions through increased congestion. Even though data for Sri Lankan conditions are lacking, study by Kanuria, Venkata, & Maitia, 2019 investigates the impact by transport sector to the sustainability in India. The paper identifies that urban congestion is causing slower traffic speeds and thereby has increased the commuting time. In Delhi city alone, traffic congestion has cost a USD 8.3 billion in 2013.

To mitigate this effect, efficient transport systems can be exercised which will support in reducing energy consumption (Liu, Zhang, Zhu, & Chu, 2017) along with mitigating traffic congestion (Dirgahayani, 2013). Therefore, initiatives such as revitalizing the public transport sector through mass transit systems are being carried out through-out the world. Mass transit systems lessens the environmental impact by emissions by reducing the single auto-mobile usage (Abdallah, 2017). A major goal of implementing mass transit is to reduce the private vehicle usage and to promote the transition from private vehicle to public transport.

This modal shift is influenced by many factors. Influence by those factors on the conversion possibility from car use to public transport use can be measured and it was identified that the most impacting factor among them are the travel time and travel cost (Altef, Mokhtarian, Ismail, & Rahmat, 2013).

2.3 Integrated Transit Systems

In literature most scholars who are examining the performance of LRTs have taken the LRT mode as a stand-alone entity and evaluated the performance. Most of the literature evaluate in terms of ridership and cost of LRT compared with bus mode transit (Kain, 1988), (Moore, 1993).

However, more recent literature is aligned towards the role of LRT or other railway transit acting as a backbone or a trunk transit and as a component of an integrated transit system. In certain literatures such as Vuchic, 2005, identifies the LRT as the backbone of a system of interconnected modes. Also, Brown & Thompson, 2008 observed that the successful regional transport systems that provide access to destinations throughout a certain region, use railways as backbone transit. Also, the literaure claims that the peformance evaluation is better balanced when the performance of the region is measured as a whole.

Thompson & Brown, 2012 have pointed out three major characteristics of a successful LRT line. First of those reasons is having a dispersed network. Such a disperesed network is arranged to serve a multitude of destinations disperesed throughout the considered region. Second of those characteristics is LRT operting atop the local bus sytem thus allowing the users to travel between dispersed origins and destination using the combination of bus and rail transits. Third characteristic that was identified was the ease of transfer beteen modes. The transfers between bus and train as well as between two buses is anabled to be achieved easily.

2.4 First Mile Connectivity

Even though the public transit has been introduced with many developments, intending the modal shift from private vehicles to public transportation, it can be seen in practical scenarios that the modal shift from private vehicle use to public transport use is minor. Kim, Jin, Park, & Kang, 2019 identifies this lag by quantifying the modal share of public transport as just 5% in the city of Sejong, Korea, where a bus rapid transit system is operating. Tilahun, Thakuriah, Li, & Keita, 2016 presents that in overall view, built and social environments between transit stations and home, work etc. are in need of attention regarding this deficiency. Kim, Jin, Park, & Kang, 2019 and Tilahun, Thakuriah, Li, & Keita, 2016 identifies that especially the relatively long distance from the homes to the bus stop being greater than what people would actually be willing to walk, is one of the key reasons for low utilization. Scheltes & Correi, 2017 on the other hand recognizes that the conventional transport modes other than walking for this segment of the trip can be slow, inflexible and do not output a seamless journey for the passenger. This spatial gap can be identified as the First mile when accessing the mass transit from origin and as the last mile when departing the mass transit system to reach the destination. First/ last mile is defined by Shen , Zhang, & Zhao, 2018 as the gap between origin/destination and heavy rail stations. By certain scholars, (Tabassum, Tanaka, Nakamura, & Ryo, 2017) and (Munoz & Hidalgo, 2013) it is observed the importance of looking at the first and last kilometer and also the connection among transport modes for the effective transit. Literature (Brons, Givoni, & Rietveld, 2009) evaluates how the easy access-to-the-station section of a rail journey influences the overall satisfaction of passengers. Therefore, it can be concluded that the first mile connectivity is of vast importance for the overall succession of the rail transit.

2.5 Feeder Modes

To supply the demand for first mile travel, effective connections are needed. These connections are identified to be the feeders which are defined in literature (Vega, 2015) as ways of linking a specific region with the backbone public transport system, usually a bus or train network or a combination of both.

Current modes that are operating in the LRT corridor are private vehicles such as cars, three-wheelers and motorcycles, para-transits and public transport mode of buses.

2.5.1 Private Vehicles as a Feeder Mode

Private vehicles are one of the modes of access that is operates as feeder modes for LRT. However, it can be noticed, that private vehicles enable by access by drop offs of the passenger. For the drivers of private vehicles to be encouraged to use the LRT, park and ride system being implemented at the LRT stations is important. However, as identified in literature (Altef, Mokhtarian, Ismail, & Rahmat, 2013) identifies that the share of private modes as feeder being as low as 1%-3% and much less than public transport for BRT stations in Sana, even though the park and ride system is provided at BRT stations. The main reason for this was identified as the lack of awareness among motorists about the park and ride system. Also, the lack of modes for the egress trip was also causing the private vehicle owners in lack of use of BRT. Therefore, it can be concluded that, to attract the passengers who will use private modes to access the LRTs, needs to be encouraged by facilities such as Park and Ride systems and eggers modes.

2.5.2 Public Transport as a Feeder Mode

The public transport modes such as railway and bus mode can be utilized as feeders to feed for higher grade transit modes. However, in Sri Lankan context, the bus mode is the plausible feeder mode for providing railway transit.

The feeder bus concept was originally developed by the real estate developers and property management companies of US to drive and forth between community area and central on a fixed route. Then that system was gradually developed in to transit feeders to improve network connections. (David & Sutton , 1995).

According to the study by Wu, Zheng, & Chen, 2008, the arrangements of 6-8 km long bus lines that surround urban railway and connects them, meets the demand and also encourage passengers who travel by walking, non-motor vehicles or taxis to move to public transport modes.

It was identified by Brown & Thompson, 2008, that it is a characteristic of a successful LRT line to be operated atop the local bus network.

2.6 Catchment Distance Calculation

The catchment area that holds the passengers willing to use the transit mode, after accessing transit mode by different feeder modes, will depend on the travel time or travel distance, that passengers are willing to travel to reach the transit by the feeder. This catchment distance may vary with the feeder mode type (Luan, Cheng, Song, & Zhao, 2019).

Ann, Jiang, & Yamamoto, 2019 identifies the catchment distance for multiple feeders by taking access distance for multiple feeders using the access distance preference by each feeder mode to access individual stations. Also taking access distance considering all the stations in a backbone transit system is another way to investigate the access distance for a feeder mode. This method was pursued by Ann , Jiang, Mothafer, & Yamamoto, 2019.

2.6.1 Stated Preference Surveys

The travel distance that is preferred by the passengers by different feeders can be identified using the surveys. For an example, Luan, Cheng, Song, & Zhao, 2019 identified the catchment distances by questionnaire surveys and face to face interviews based on random households in the in relevant TAZs in the corridor of the transit line. Travel information such as trip purpose, trip OD and travel times were identified. The travelling modes such as walking, cycling, bus to reach the Urban railway transit that was considered in their study.

The study by Balya & Kumar, 2017, considers the walking mode as feeder to the BRT of Ahamadabad city. To identify the walking distance preference, the residents in the corridor in the BRT were interviewed by home interview study, using face to face technique. The residential area of interview was limited by considering the corridor that was adjacent to the BRT.

Another study (Cherchi & A. Hensher, 2015) states that stated preference surveys as a way to identify the behavioral information on preferences of individuals and groups. The research further analyzes the challenges related to design and implementation of SPS surveys and how to improve he SPS surveys.

2.6.2 Catchment Distance Identification

After the preferred catchment distances for different feeder modes are identified using the surveys, a value that represents the feeder mode for access distance preference can be identified using the data set. For this purpose, the variation of the data set and a certain justifiable percentile value can be identified, to represent the whole data set.

Ann, Jiang, & Yamamoto, 2019 identified this threshold walking distance by using the values mean and the 85th percentile of the data set of walking distances. The receiver operating characteristics curves were used for this purpose. When considering the different stations and identifying this value, there were no significant variations in the values. But for other modes rather than walking, there were large variation in the mean and 85th percentile values in different stations.

The study Ann , Jiang, Mothafer, & Yamamoto, 2019 again pursues this variation by selecting mean and the 85th percentile values. In this study, the access distance variation for different feeders was the focus rather than the variation of access distance with the station.

The report by Wakenshaw & Bunn, 2015 on the distance that people walked which was presented at PTRC Transport Practitioner's meeting in London, uses two methods, namely weighted average method and the 85th percentile value method to identify the distance that people preferred to travel by walking.

Taking the 85th percentile value to take a threshold value representing the access distance was identified to be followed in several more studies such as Hochmair, 2014 and Zhao, Chow, Li, Ubaka, & Gan, 2003.

2.7 Catchment Area Calculations

The size and the shape of the catchment area will be determined by the distance to/ from the transit station. Those areas can be identified either by circular buffer approach or service area approach (Andersen & Landex, 2009). In both cases the buffer or the service area can be constrained by the travelling time or distance limitation. However, when comparing the two approaches several advantages and disadvantages can be recognized as seen in their study. It can be seen that the circular buffer approach, over-estimates the size of catchment area.

Catchment area can be identified as the service area that depend on the route travel time constraints according to Jerby & Ceder, 2006. Even though the base network of roads is extent, the links that cannot be covered in the time allocated for the travel should not be considered. Following Jerby and Ceder, the zones that has the shortest path connecting to the transit center, which exceeds the travel distance or time constraints, has to be eliminated from the grid. Therefore, in this study, for each feeder mode, a travel distance that is preferred by the passengers for that particular feeder mode, can be identified to identify the service area constrained by that travel time or distance.

2.8 GIS Software Usage for Catchment Area Identification

According to the definition by the Esri Arc GIS and by Vitosoglu, Gungor, & Yaliniz, 2017, GIS are computer-based systems, which are employed for capturing, storing, manipulating, demonstrating and analyzing the graphical and non-graphical information, which are based on locations. As per Yomralioglu, 2000, as GIS provides multiple functions within its environment, the users are not required to master different and specialized technologies. Therefore, the use of GIS is adopted by many organizations, worldwide.

Andersen & Landex, 2009, uses GIS based catchment area analysis in their study in 2009. Both service area catchment and the circular buffer area catchment can be identified by the GIS software. Also, the geographical and road network limitations, that will affect the catchment area can be recognized in the GIS software easily.

Therefore, to identify the LRT corridor, where the potential transit rider passengers are, can be identified using the GIS software. For an example, the study by Gahlot, Swami, Parida, & Kalla, 2012, identifies the BRT corridor for Jaipur city using the GIS environment.

2.9 Bus Route Accessibility

While the catchment area of a feeder depends on the travel distance or time that is preferred by passengers, other factors such as the accessibility enabled by the existing bus routes may also affect. This accessibility can be evaluated using the Conveyal model. As per references such as Currie, 2021), Conveyal is a valid tool for accessibility measurements by public transport.

2.10 Conveyal Model

Conveyal analysis is an open-source application, which evaluated the accessibility of public transport networks and the changes to public transport modes can also be evaluated using accessibility indicators. A time constraint can be defined when analyzing the accessibility and scenarios of walking and using motorcycles to reach the public transport modes are considered. The route alignment, speeds, frequencies can be changed to evaluate the changes in the accessibility and adding or removing routes can also be carried out.

The public transport modes such as buses, railway, LRT, Monorail, tram, ferry are investigated.

2.11 Transit Planning

Through identifying the catchment area for bus feeder and the coverage by the existing bus network, it is clear that the structure of the present bus network is unsuitable to provide the connections between the origins and the LRT stations. Therefore, a further investigation into bus network design is pursued.

2.11.1 Objectives of Transit Planning

As a solution for the worsening traffic congestion in the world, the world community is encouraged to use public transit rather than the private modes. However, for an efficient and effective transit system in urban context, the transit network should be able to provide accessibility to the focused service area, with transport systems that enhance comfort, convenience and safety (Lee & Bencekri, 2020).

Therefore, in the context of this study, the LRT and bus modes are the public transit modes. To enable the transit from origin to destination, the soundly connected network with the maximum efficiency is required. However, the resources for public transport are limited as well. Therefore, the main problem in public transit network design can be identified as the balance between the user cost and operator cost. Effective design of transit and service frequencies will reduce the overall cost of transit providence, which consist of user and operator costs (Sirisoma, Bandara, & Kumarage, 2002). The problem of this optimal balance is the key objective in many studies by authors such as Kuah & Perl, 1987.

However, the objective of a social responsibility of the transport agencies towards supplying the required transport also might weight in.

2.11.2 User Cost

Generally, the user cost, which is occurred by the traveler, include the in-vehicle time and transfer time. Also, the access cost can be taken into account. The passengers would prefer to minimize the travel time and the cost related to the travel. Therefore, it can be reasonably assumed that the passengers would prefer to use the minimum travel path to the destination (Sirisoma, Bandara, & Kumarage, 2002). In fact, traveler would want to travel at anytime and as fast as possible from the origin to the destination. Such a network will have very high frequencies and high speeds (van Nes & Bovy, 2000).

2.11.3 Operator Cost

Operator cost on the other hand consists of the cost of providing the service. Operator costs include the

Form the operator's point of view, operators would prefer to maximize the profit with a high demand level but minimize the costs by limiting the travel distance (van Nes & Bovy, 2000).

Therefore, the focus of most of the studies of transit design is about the optimal balance between the above costs.

2.12 Bus Network Design Approaches

It can be seen through the literature that the studies have been carried out for bus network design and optimization purpose. While most of the studies, for an example Shih, Mahmassani, & Baaj, 1998 and Sirisoma, Bandara, & Kumarage, 2002 are based on designing a general transit network for a certain geographical area, some of the studies such as Sirisoma & Bandara, 2002 and Sirisoma & Bandara, 2005 are specified as primary route design and some studies such as researches by Zhu, Guo, Zeng, & Zhang, 2016, Jerby & Ceder, 2006, Kuah & Perl, 1987 are specified for feeder route design. For this study, all those aspects are looked upon to investigate the feasibility of integrating the primary and feeder networks in to one network where a backbone mass transit and feeders will operate, replacing the primary network.

The studies can also be observed to be either mathematical model developments or studies where heuristic approaches are suggested for transit network development.

As another perspective, certain studies such as Chandra, Bari, Devarasetty, & Vadali, 2013, can be identified as transit designs of fixed routes and transit designs where both fixed regular routes and feeder routes are co-existing.

2.12.1 Mathematical Models/ Simulation Models

Various designs of bus routes to supply for a certain geographical area can be dated back to 1980s. From these studies, several studies can be identified to be based on mathematical modeling, which develops bus route networks and optimize them by programming models and stimulating them. For an example Marwah, Umrigar, & Patnaik, 1984.

The study by Narayan, Cats, van Oort, & Hoogendoorn, 2020 expands the vision on program based public transport design by multimodal route choice and assignment model that allows the users to combine the fixed and flexible public transport routes or to use them individually. The model was applied to the city of Amsterdam, and the results indicate that the flexible public transport is used only for covering less than 30% of the trip length, which indicated that flexible routes are more inclined towards being used as access or egress mode for fixed routes.

2.12.2 Heuristic Approaches Transit Network Design

Shih, Mahmassani, & Baaj, 1998 presents a heuristic model for the design of bus transit networks with coordinated operations, where the significance lies in the coordination. Most of the transit systems that are studied are uncoordinated. However, Shih et al. presents a network with coordinated operations where operations are focused on a transit center concept. The design model follows 4 steps, and they are demonstrated on the case study of existing transit system in Austin, Texas. The 4 steps are,

1. Route generation procedure (RGP) – constructing transit network around the center
2. Network Analysis procedure – trip assignment, frequency setting, vehicle sizing
3. Transit center selection procedure
4. Network improvement procedure

Sirisoma, Bandara, & Kumarage, 2002 develops a methodology to develop a transit network for the Western Province, Sri Lanka. The process was carried out in steps as follow,

1. Optimum route network. This network was developed using the minimum spanning tree
2. Route Generation based on demand. The route generation was proceeded following the highest demanding OD pairs
3. Route alterations. The assigned routes in the second steps were optimized by route merging, route breaking etc.

Sirisoma & Bandara, 2002, identified a methodology to plan a primary route network for a region. This study also followed the steps of identifying the OD matrix and then using an algorithm to generate the initial route network based on demand and minimum path rule and the constraint of each node being served by at least one route. Here, the focus was on the primary routes, which are routes connecting DSDs.

2.12.3 Feeder Mode Specified Network Designs

The feeder bus route design can be similar to the primary route design with certain special aspects. Feeder route design also has been carried out in mathematical models and heuristics models.

Kuah & Perl, 1987, has pursued on feeder design from as early as 1987. They also have considered the balance problem of user cost and the operator cost. The many to one demand is discussed under a mathematical problem. However, the design of the bus network and the frequency assignment has been carried out heuristically. The study was two-fold. First step was to identify the route, which was conducted using a M-to-1 model and then frequencies were assigned using the objective function which minimizes the user and operator costs.

Jerby & Ceder, 2006 also look into the shuttle bus service design, which will operate as the feeder network. Their study has been carried out in three steps. First step was to estimate the demand for a certain bus route. Second step was developing an operational research model which focuses on optimal route design. And the final step was developing a heuristic algorithm which is an alternative to the optimal model. The two alternatives were compared by applying on small road networks. The results showed that the heuristic approach yielded the optimal results. This heuristic approach was then implemented in medium and large networks, which again outputted good results.

In both approaches by Jerby and Ceder, 2006, the street network that can be utilized for bus network was identified by filtering out the links that exceed the time constraint. The recognized links were assigned with a demand that was identified based on population density and the walking distance. After assigning a demand. Each link was again given a priority index, which will show the importance of that link being included in a bus route. After developing this base network, the optimal network was analyzed by the two alternatives, analytical programming method and the heuristic method.

Zhu, Guo, Zeng, & Zhang, 2016 also studies into feeder bus route design specifically, testing their design on a community in Shanghai. They developed a mathematical model to design the optimum route network. Demand was identified for each zone in a grid and the links that passes through the zones were assigned with the demands. The probability of a link being assigned with demand has also been considered. By assigning links with demands, feeder routes were identified, and the model maximizes the demand of passengers while complying with the travel time constraint by an iterative method.

A bus feeder network can be designed to cater to the demand of the catchment area. However, the problem in feeder bus design, can be observed as achieving the optimal balance between operator and user costs. In all above studies, it can be seen that this problem is pursued as they all consider the demand and route length as key factors in their studies.

From the above studies, several steps can be identified to be distinguished. One is the base network identification considering the route lengths. Second one is the demand assignment. Final step was to optimize the network. Though it is for a primary network or specifically for a feeder network, these steps can be identified.

As a further step, the designs with fixed and flexible routes both operating can also be investigated upon. As observed in Narayan, Cats, van Oort, & Hoogendoorn, 2020, the design can be a dynamic model which will have evolving routes based on the dynamic demand. Presently in Sri Lanka, there are no demand based flexible public transport systems. however, if the dynamic demand can be generated, a system which will model route choices and then load the network with the demand can be carried out as proposed by Narayan, Cats, van Oort, & Hoogendoorn, 2020. however, in the practical application of the study, it was identified that the fixed routes are plausible for more than 70% of the trip lengths of the passengers. Only 30% of the trip lengths at the beginning and the end were determined to be flexible. Therefore, a transit network with fixed primary network and flexible feeder routes may be developed with the dynamic demand data availability.

Chandra, Bari, Devarasetty, & Vadali, 2013 evaluates the accessibility impacts of having feeder connectivity to/from major transit by fixed route transit and demand responsive transit both. The higher demands will be responded by the fixed routes and the lower demands by the demand responsive routes. This study aims for an equilibrium where the demand will be satisfied by increasing the stops of feeder buses while avoiding unwanted increase in waiting and riding times of passengers.

2.13 Network Design Steps

The network design steps that were followed in literature can be observed by referring literature such as, Sirisoma, Bandara, & Kumarage, 2002, Sirisoma & Bandara, 2002, Shih, Mahmassani, & Baaj, 1998, Li, et al., 2019, Jerby & Ceder, 2006, Zhu, Guo, Zeng, & Zhang, 2016 etc. which are further discussed in the Chapter 3.

2.14 Innovative Solutions

The previous design criteria that were discussed were focused upon fixed feeder routes. However, as a further step, flexible and demand responsive feeders can be further investigated upon. This will be an effective solution for the resource limitation.

However, to enable this type of customized bus service, the passengers as individuals are required to be involved with the service design process. As identified in Tong, Zhou, Liu, & Zhou, 2017, the operating procedure in a demand responsive feeder network will start by collecting travel demand and the submitted demand will be matched with the available customized bus routes. This may be done through the software applications and the payments can be processed through the them as well. The unsatisfied demand requests were noticed that requires addressing, whose unsatisfied requests will be processed, and optimization procedures can be carried out based on them. For an example, when the number of passenger demand requests reach a certain limit, a new customized route may be implemented.

Narayan, Cats, van Oort, & Hoogendoorn, 2020, is another study that focuses upon the flexible public transportation and the efficiency in combining the fixed and flexible public transportation. Theis study identified that the efficiency of the whole system is higher, when the flexible public transportation routes operate as feeders to the fixed transit lines.

3 Research Methodology

The research methodology was organized, with the aim of fulfilling the objectives of the research. The main objective of this research is to construct a methodology or a process to develop a feeder bus network for a Light Rail transit system in Sri Lanka. Further to apply it for Fort – Malabe line as a case study.

Hence, the research methodology was identified as in following steps.

Step 1: Identifying the requirement of bus feeder networks for LRTs

Step 2: Identifying the methodologies followed for developing bus feeder networks for backbone transit systems

Step 3: Identifying the methodologies for Bus Network development from literature

Step 4: Identifying the data requirements for Feeder Bus Network design

Step 5: Identifying a methodology for developing bus feeder network for a LRT in Sri Lanka

Step 6: Applying the identified methodology for Fort – Malabe corridor

3.1 RESEARCH METHODOLOGY STEP 1: Identifying the Requirement of Bus Feeder Networks for LRTs

In the literature review, the requirement of feeders and most importantly the bus feeder system to operate along the LRT was identified (Brown & Thompson, 2008, Brons, Givoni, & Rietveld, 2009, Wu, Zheng, & Chen, 2008). It was clear that for the LRT line to work in an intergrated transport system as a back bone transit and to operate successfully, the connections enabled by feeders on first and last mile is vital. The connections between origins and destinations and the LRT access points inluence heavily the ridership of LRT line and the regional transoit network as a whole.

Further more, the feeder modes and their modal share have been investigated in the literature. From undertanding the feeder mode share and demand for bus feeder, the requirement of a bus feeder network has been identified (Tabassum, Tanaka, Nakamura, & Ryo, 2017).

3.2 RESEARCH METHODOLOGY STEP 2: Identifying the Methodologies for Developing Bus Feeder Networks for Backbone Transit systems

Referring the literature, certain methodologies for developing a Feeder Bus network for a backbone transit system has been proposed for some other countries. For an example, in Lahore, Pakistan, a methodology is proposed for developing a Feeder Bus network for the BRT system currently operating in Lahore by Tabassum, Tanaka, Nakamura, & Ryo, 2017. For Lahore BRT service, a dedicated feeder system is not implemented. Hence, in the study, they are examining the requirement of a feeder, and what type of feeder mode to initiate and propose strategies to initiate feeder services.

In their methodology, they are proposing the methodology in several steps as follows.

I. Examining the need for starting a Feeder service
II. Assessing the feeder modal share and the quality of feeders as perceived by users
III. Spatial analysis of service area of feeders
IV. Proposing strategies which include selecting the areas for feeders to enhance the accessibility which is evaluated and to maintain the travel impedance at the minimum and thereby initiating a feeder service

3.2.1 Examining the Need for Starting a Feeder Service

The referred study requires data regarding transit mode and feeder, usage and travel times and the user's perception towards the quality of the feeder modes in areas such as cost, comfort, reliability, and safety. From those data, the study has analyzed the requirement of feeders in accessing the backbone transit mode and the feeders.

3.2.2 Assessing the Feeder Modal Share and the Quality of Feeders

In the study, it was identified that most users that are willing to use the transit are not supplied with a feeder to access the backbone transit. And by evaluating the feeder modal share and the quality of those feeders as perceived by the users, the study has verified that buses that are currently available as the public mode, serves as a feeder for BRT and also that most users do not have the accessibility to reach the bus feeder even though they are willing to use the bus feeder. Therefore, it was identified that the bus feeder network needs further attention to be improved as feeder network.

3.2.3 Spatial Analysis of Service Area of Feeders

A spatial service analysis has been carried using Arc Map 10.5, to evaluate the existing bus feeders by showing the bus stops in the study area and showing a buffer area of 500m, assuming the walking distance from each bus stop to be 500m. Hence, the area that has the accessibility to reach the backbone transit can be evaluated.

For this spatial service analysis, the researchers have used the link network data of the study area as well as the existing regular bus route data.

3.2.4 Proposing Strategies for Initiating a Feeder Service

After identifying the requirement of a developed feeder bus network, the study has proposed strategies for feeder network design.

The proposed strategy initially identifies the potential areas in need of a feeder network. It was deemed that the areas in most need require to be identified as feeder services are required to go through the areas generating most riders while keeping the impedance of the feeder service minimum. Therefore, this study has looked at the percent of the population with and without accessibility and also other land use factors. The population density is the most important land use factor identified, along with the population distribution patterns within an area.

Secondly, the proposed strategy uses a gravity-based accessibility model proposed by Zhu & Liu, 2004 to estimate the potential accessibility of a destination, based on attarction from origin and impedence betweeen origin and destination.the travel impedence has been factored by reliability, travel time, travel cost, comfort, safety and environmental aspects. Furthermore, the calculation gives an optimum number of stops to be implemented in a route between the considered origin and the destination.

The study concludes and proposes to redesign/realign the exising public transport feeder to increase the coverage, following the proposed strategy.

3.3 RESEARCH METHODOLOGY STEP 3: Identifying the Methodologies for Bus Network Development from Literature

In the previous section 3.2, a methodology that had been followed to propose a Feeder Bus Network for a BRT in Lahore was discussed. Furthermore, the literature that was referred, follows certain guidelines in designing Bus Networks even though they are not specified as Feder Bus Networks.

For Sri Lanka, even though attention has not been given upon designing Feeder Bus Networks, several studies have been conducted on designing the Bus Networks for regions. Those guidelines or steps were further investigated to understand the procedure that has been followed in the literature. As a summary, the identified steps were as below.

I. Link network development
II. Area demand identification
III. Ranking of demand
IV. Bus route path identification by GIS
V. Route implementation
VI. Network optimization

3.3.1 Link Network Development

The first step was identified as constructing a base network of links. According to Sirisoma, Bandara, & Kumarage, 2002 and Sirisoma & Bandara, 2002, the link network was developed by the considering the existing road network and considering every link in the network. Beginning with any node, the shortest possible path was identified to the closest node. Thereby, the unconnected nodes were connected by the shortest path again to a connected node. In that manner an optimum network was identified.

In most studies the Skelton network was developed using the minimum distance method.

In route generation feat, Shih, Mahmassani, & Baaj, 1998 has followed on by constructing a Skelton structure of a network based around the transit center. The initial formation is based on the demand. The highest demanded pairs are first connected. Therefore, high demanded nodes are connected directly. A route layout termination was carried if the number of routes exceeded a certain number.

3.3.2 Area Demand Representation

In the study by Shih, Mahmassani, & Baaj, 1998, after developing the route network from the skeleton structure, the second feat was the network analysis procedure, where demands were assigned to the routes and frequencies were assigned. To identify the demands that to be assigned to each link, the demand from the zones in the service area is required. The demand will depend on the potential transit ridership. These demand values can be taken zone wise. As per the study by Ramirez & Seneviratne, 1996, these zones may be a census track, block, block group or any other area where disaggregate information is available.

Li, et al., 2019 found out the population density and the common residence land to be the dominating factors affecting morning boarding traffic and the evening alighting traffic in railway of Guangzhou province, China.

On the other hand, as per Jerby & Ceder, 2006, recognized that the demand at a link in the road network is based on the population density and the area included in the walking distance from that link. This procedure is also accurate as the demand for a certain bus route will depend on the population that can access the bus route directly.

Zhu, Guo, Zeng, & Zhang, 2016, identified the demand of each link to be proportional to the traffic demand of the relevant aggregated area and also the distance between the link and the railway station. They introduced an equation to calculate the demand at each link, which factored the travel demand by the area, average distance that potential passengers to travel to the link, the distance from the link to the transit center and other coefficients.

Vitosoglu, Gungor, & Yaliniz, 2017, proposes an OD matrix based on multiple factors. The demand by each link is determined by the estimated trip generations by simultaneous linear equations and probability of those trips passing through the link.

3.3.3 Ranking of Demand

According to Rupi, Angelini, Bernardi, Danesi, & Rossi, 2015, the links can be ranked by their importance in maintaining the connection between all OD pairs. To measure the importance, a index which weights the contribution of the link by the usage (Local Importance) and the severity of consequences on the entire network by the closure of the link (Global importance) was determined. A formula for link importance was introduced with the calibration coefficients, therefore the usage of links may be calibrated as per the requirement (Rupi, Angelini, Bernardi, Danesi, & Rossi, 2015).

3.3.4 Bus Route Path Identification by GIS Environment

The public transportation network is characterized by the requirement of meeting several objectives, such as maximizing the coverage while minimizing the travel time by the public transport. According to Ramirez & Seneviratne, 1996, GIS can be utilized to apply those multiple and contrasting objectives to bus transit. According to the study, they have identified methods to use a direct demand model to generate routes by an impedance function, which follows the constraint of shortest path and a second method to improve the transit routes, so it serves the large centers better.

Vitosoglu, Gungor, & Yaliniz, 2017, proposes to transfer the OD matrices to GIS environment in order to evaluate the information.

3.3.5 Route Implementation

In route implementation, a set of guidelines were carried out in the study by Shih, Mahmassani, & Baaj, 1998. The eligibility of a node for a route is determined by the following criteria. (a) resulting routes does not form a loop (b) the node having a percentage of its demand satisfied directly (c) route not being circuitous (d) the ratio of demand and route insertion cost exceeds a preset, (e) frequency does not exceed a maximum operational value, (f) round trip time of roue does not exceed a maximum value.

The order of route implementation was demand based according to Shih, Mahmassani, & Baaj, 1998. Again 4 guidelines were followed, where the route were promoted to be inserted in the order where a maximum demand will be satisfied with the increase of in vehicle time (route lengths).

3.3.6 Assumptions

The constraints that were followed in several studies which are valid for this study were identified as follow.

Assumptions of Sirisoma, Bandara, & Kumarage, 2002 in the algorithm to determine the optimum route network are as below.

- The demand pattern is static and remains constant for all periods of study.
- A passenger will choose the route based on the shortest travel time.
- Every bus travel with constant speed.
- Travel demand is symmetric in the system.
- Routes can have partial overlaps.
- All buses are in the same capacity.
- All buses are in good condition and all buses operate for all 30 days per month

3.3.7 Network Optimization

In the study by Shih, Mahmassani, & Baaj, 1998, the final step was about network improvements procedures. The improvements were carried out by route discontinuation, route merging, route splitting, branch exchange of routes, demand responsive services etc.

Route modifications such as route merging, breaking, sprouting can be seen in other studies such as Sirisoma, Bandara, & Kumarage, 2002, Sirisoma & Bandara, 2002 as well. Those studies identify the methods such as route merging, breaking can be applied with examples.

For route merging, Sirisoma, Bandara, & Kumarage, 2002, identifies that it can be carried out in the scenario of several routes terminating at the same node and when there are several possible ways to join the routes. However, criteria that needs to be observed such as demand per unit density, are also mentioned in the study for cost effectiveness.

For route breaking, again Sirisoma, Bandara, & Kumarage, 2002, notes that it can be done for routes having significant variation in demand throughout their path. Thereby, the links with the higher demands can be split into a separate route. The lowest demanded routes will also become a separate route.

Sirisoma, Bandara, & Kumarage, 2002 and Sirisoma & Bandara, 2002 identifies the route sprouting option as well, where routes will overlap in certain links to accommodate the high demand in those links. This may occur where there is a high fluctuation in demand and a certain link having a high demand relative to other links. In that case, the high demanded link will be operated as a separate route.

3.4 RESEARCH METHODOLOGY STEP 4: Identifying the Data Requirements Feeder Bus Network Design

In the literature, the feeder modes preference by LRT users were investigated and the travel times or distances that the passengers are willing to travel to reach the LRT access points using each of the feeders were identified to calculate the catchment area by a feeder mode. Hence, the first data requirement was identified as the travel times/ distances passengers willing to travel using the feeder modes and in this study's case especially by bus feeder mode.

Furthermore, in literature, the road links in the study area, along with Socio-economic indices of Transport Analysis Zones in study area were identified to be required.

The evaluation of bus feeder designs in the literature was identified. It can be seen some literature has evaluated the design using the accessibility (Tabassum, Tanaka, Nakamura, & Ryo, 2017) while others refer to the ridership performance to evaluate a LRT (Thompson & Brown, 2012).

3.5 RESEARCH METHODOLOGY STEP 5: Identifying a Methodology for Developing a Bus Feeder Network for a LRT in Sri Lanka

A methodology for developing a Bus Feeder Network for a LRT in Sri Lanka was identified by referring the literature on Bus Feeder Network development and the literature on Bus Network development both and combining the processes.

The identified methodology is discussed in Chapter 4.

3.6 RESEARCH METHODOLOGY STEP 6: Applying the identified Methodology for Fort – Malabe corridor

The application of the identified methodology to the Fort – Malabe LRT line is discussed in Chapter 4.2.

4 Analysis and Discussion

4.1 Identifying a Methodology to a Develop Bus Feeder Network for a LRT in Sri Lanka

The literature that was identified in Chapter 2 and specially in Chapter 3 were used to construct a methodology to develop feeder bus network for a LRT in Sri Lanka.

In this process certain steps that were identified in feeder bus network designing for backbone transits in other countries were integrated with the bus network design studies conducted for Sri Lanka, which aims to develop bus transit networks for a certain region.

Furthermore, the GTFS format and the Conveyal analysis which were discussed in the Literature Review, were also combined into the identified methodology.

The identified methodology is in below sequence.

1) Data collection
    - Feeder mode types of the study area
    - Data on feeder mode preference
    - Data on travel time and/or distance preference
    - Socio economic indices of the study area
    - Road link network data
    - Current bus route data
2) Examining the requirement of a feeder network
    - Using the collected data on travel time and/or distance preference, catchment distances that is preferred to be travelled by each feeder mode is analyzed
    - The catchment areas of different feeder modes are calculated
    - Hence the demand for a feeder network is examined
3) Assessing the modal share
    - The data regarding the feeder mode preference
    - The preferred modal share of different feeders is analyzed
    - Thereby the importance level of bus mode as the public feeder mode type is identified

4) Analyzing bus catchment area and accessibility by present bus feeder mode
    - The road link network of the study area is identified
    - Using Arc GIS 10.5, the catchment area of bus mode is analyzed and visualized. Hence study area is defined
    - Current bus network data are structured in to GTFS format
    - Using Conveyal analysis the accessible areas by current bus network is analyzed
    - The areas inside the catchment yet not accessible by the present bus mode is identified
5) Applying Bus Feeder Design Method strategies
    a. Design method 1: Modifying the existing bus network

       Design method 1 focuses upon the areas inside catchment area that is not supplied by the present bus routes. Existing bus routes are modified, and new routes are added for the areas that are not accessible by present bus routes
    b. Design Method 2: Designing the bus network

       Design method 2 focuses on the whole catchment area. In this method, the present bus routes are not operating, and a new bus network design is developed for the study area
    c. In both design methods, the following steps are followed
        i. Identifying the spatial area requiring the feeder design. In Design method 1, the spatial areas that is not accessible by present bus routes and in Design method 2, spatial area bounded by catchment
        ii. In each design method, GNDs of the identified areas are identified
        iii. In each design method, the centroids of the identified GND shape area are located
        iv. In each design method, the shortest path links from each demanding GND centroid to the nearest LRT are identified
        v. In each design method, bus routes are implemented in each identified shortest path
6) Evaluation of accessibility by different Strategies
    a. In each design method, the accessibility is evaluated by the area that is accessible
7) Selecting the suitable strategy

8) Optimizing the selected design
    i. A bus route grid is developed
    ii. The demand incurred by each GND is calculated based on area and population density
    iii. GNDs are ranked by their demand for the feeders
    iv. Demand is assigned to the developed grid following the sequence of ranking
    v. The design is optimized using route merging, route breaking etc.

4.2 Application of identified Methodology to Develop a Feeder Bus Network – Case Study of Fort – Malabe LRT line

For the Fort – Malabe corridor, the proposed LRT line and the access stations are discussed in the introduction. The feeder modes that will feed the proposed LRT by connecting residential areas with LRT stations, thus enabling the passengers willing to travel from catchment areas to reach the LRT are identified. In this corridor, currently feeder modes that can be identified are, walking and cycling, private vehicles, para transit and bus transit. A railway that can be feeding the LRT cannot be identified in this corridor. Considering the transport development conditions and master plans for the considered area, the future feeder modes are not anticipated to be different from the current feeder modes.

4.2.1 Data Requirement

The first step was to identify the catchment distances and areas of the Fort-Malabe LRT for different feeders. Therefore, the data requirement was identified as the data that can be used to identify the origin areas, LRT station characteristics and determine the travel distance that the passengers by different feeders are willing to travel by the respective feeder mode. Therefore, a data survey surveying the travel data of trips reaching the LRT station locations from adjacent origins of the Fort-Malabe corridor is required.

Furthermore, in designing a bus feeder network, the road links in the fort – Malabe corridor, GND data were identified to be required. In GND data, the shape area, population, HH data and trip generation rates were identified to be important. Also, a measure of preference for each feeder mode was also required to identify the distribution of demand for feeder types from the population in the GND.

For the feeder network optimization, the population characteristics of the catchment was determined to be required.

To identify the characteristics of LRT stations and origin areas and the extent of origin area spread, a preliminary study of the concentrated corridor is required. Therefore, an initial survey evaluating the LRT corridor and the potential catchment area was carried out. The locations of the proposed LRT stations, the nearest town/village to the station, the road networks that connects LRT stations with adjacent areas and the potential towns/villages that can be expected to be included in the catchment were identified by a visual survey using an administrative map. Therefore, characteristics of each proposed LRT station were identified visually. It was identified that the corridor in consideration had multiple geographical boundaries, varied land use, a road network with limited higher classed roads and a bus network operating in limited routes.

4.2.2 Data Sourcing

To obtain the required data, the options of carrying out a data survey or utilizing an available data survey were considered. A stated preference survey was the survey type that was identified as the suitable. By a stated preference survey, the aspects such as the mode of access, travel origin and destination, travel time, cost and other factors valued by passengers are quantified.

When the available data was inquired for, it was observed that in order to carry out the JICA LRT preparatory report, a stated preference survey of the relevant corridor has already been carried out and the survey data are available for access. The survey has considered 23 survey locations as LRT stations. Out of the referred survey locations 15 coincides with the proposed LRT station locations as shown in Table 4.

Table 4: Survey locations and relevant LRT stations

Survey location	Station loation
Kotahena	
Armour Street	
Sebatian Canal	
Keselwatta	
Fort	Fort
WTC	
Slave Island	
Union Place	Union Place
Maradana	Maradana
Sethsiripaya	Sethsiripaya
Lumbini Temple	Lumbini Temple
Punchi Borella	
Talahena	Talahena
Cotta Road	Cotta Road
Welikada	Welikada
Malabe	Malabe
Rajagiriya	Rajagiriya
Battaramulla	Battaramulla
Robert Gunawardana Mawatha	Robert Gunawardana Mawatha
Palan Thuna	
Dayawanna Lake	
Town Hall	Town Hall
Borella	Borella

The survey which was conducted in 2014 has surveyed households within 1 km from the corridor. The survey was primarily undertaken to understand the willingness to pay for new transit systems. The relative importance allocated on various attributes of the journey by a new transport system, by the potential users was aimed to be estimated. The attributes that were considered are travel time, travel cost for the new transport system and the access and egress information which is also the data requirement of this study. Therefore, the stated preference survey carried out for JICA LRT preparatory survey (Japan International Cooperation Agency, 2018) was determined as the data source.

The complete survey details are as follows.

1. Purpose of travel
2. Origin/Destination
3. Time
4. Means of travel
5. Assuming that monorail is available and the passenger being interviewed is using it,
    a. Nearest station to origin
    b. What mode of transport you would most likely use to get to the nearest station?
    c. How much would you pay to go to the nearest station?

d. How long do you think it would take?

e. Average waiting time at the station is

f. The nearest station to your trip destination is

g. What mode of transport you would most likely use to get to your destination?

h. How much would you pay to go to your destination and how long do you think it would take?

i. Travel time of Monorail from the station nearest to your origin to the station nearest to your destination is

j. If you use the Monorail, how long is your total travel time from the origin to the destination including travel time by all other modes of transport, waiting time, and transfer time?

k. Do you change your current mode of transport to Monorail if it starts operation?

The survey consists of data samples from 614 passengers. Out of the total sample, only 551 samples consisted of complete data regarding the access and egress. As the objective was to identify the catchment areas, access segment of the trip was the focus in the survey data. Therefore, the utilized data were,

- Nearest LRT station to the origin
- Preferred access mode
- Access travel time expected by the passenger to reach the nearest LRT from the household

From this survey, the travel times preferred by passengers in each feeder category were identified. Also, this survey gives an understanding on how the demand for different feeder types varies as well.

By the stated preference survey, the access travel time expected from origin to the nearest LRT can be identified. However, the requirement is the access distance. Therefore, in order to convert the travel times to travel distances, the speeds of the corridor were considered.

For this feat, the Post Graduate thesis by Mr. Sakitha Kumarage (Kumarage, 2018) was referred. For his master's thesis, a speed survey carried out in the Fort- Malabe corridor in June of 2019 was employed. This speed survey considers the corridor in sections as in the Table 5.

Table 5: Lengths of Road Section for Speed Survey

Road Section	Link Length (m)
Fort – Maradana	3549
Maradana – Union Place	4548
Union Place – Townhall	840
Townhall – Borella	1452
Borella – Cotta road	567
Cotta road – Welikada	2565
Welikada – Rajagiriya	806
Rajagiriya – Sethsiripaya	1660
Sethsiripaya – Battaramulla	1435
Battaramulla – Robert Gunewardhana mawatha	1253
Robert Gunewardhana Mawatha – Lumbini temple	1316
Lumbini temple – Thalahena	968
Thalahena – Malabe	1357
Malabe – IT park	940

Using crowdsourced data mining, Travel time data for each link (segment) has been collected from 6.00 am to 9.50 pm at every 10-minute interval for the weekdays (Monday - Friday) for both directions as shown in Table 6. From the survey results a flow speed throughout the day can be identified.

Table 6: Speed Data for the Links in Speed Survey

	Speeds of the segments (km/h)														
Time	Batthara mulla-Sethsirip aya	Borella_ National Hospital	Cotta Rd-Borella	IT park-Malabe (Bus Stand)	Lotus tower-Fort	Lumbini Temple-Robert Gunewar d	Malabe (Bus Stand)-Talahen a	National Hospital-St.Josep h	Palam tuna-Batthara mulla	Rajagiriy a-Welikad a	Sethsirip aya_Raj agiriya	St.Josep h-Lotus tower	Talahen a-Lumbini Temple	Welikad a-Cotta Rd	Average speed of the corridor (km/h)
6:00:00 AM	17	20	22	33	10	41	31	16	26	36	27	22	33	22	25
6:10:00 AM	17	20	21	29	10	40	29	15	25	34	24	21	31	21	24
6:20:00 AM	17	20	20	27	10	37	28	14	25	30	20	21	29	19	23
6:30:00 AM	17	18	19	27	9	36	29	14	24	24	17	21	30	15	21
6:40:00 AM	17	17	17	23	9	36	27	13	25	16	12	20	30	12	20
6:50:00 AM	16	17	15	18	9	35	27	12	25	12	10	19	29	9	18
7:00:00 AM	16	14	14	14	10	33	26	12	25	11	9	18	28	8	17
7:10:00 AM	16	13	13	12	11	31	25	11	24	11	7	17	26	8	16
7:20:00 AM	16	11	12	12	11	29	25	10	23	11	7	16	25	8	16
7:30:00 AM	16	10	11	16	11	28	25	10	23	12	6	16	25	8	15

4.2.3 Development of Data

The collected data were further evaluated for the accuracy and the relevance for the research scope. The identified sample in stated preference survey (Japan International Cooperation Agency, 2018), was of the size of 612 samples which is a considerable number of samples and of an adequate size. Also, it contains the data samples from passengers that are currently using different modes of transport to reach the destination from the origin thereby more effective due to the inclusion of samples of varied categories. The number of samples by the current mode of travel from origin to destination is shown in Table 7 .Regarding the relevance of the data, it can be understood that the data were collected in a 1km distance belt from the Fort-Malabe corridor and thereby the collected data were from relevant areas.

Table 7: The number of Samples by the Current Mode of Travel from Origin to Dest.

Travel mode	Number of passengers using the travel mode to reach the destination from origin at present
Public transport	366
Motor cycle	99
Private Three wheelers	23
Cars	124
Total	612

The data were further developed to cater to the research needs. From the stated preference survey of JICA LRT preparatory survey report (Japan International Cooperation Agency, 2018), information on the access trip to reach the LRT by the feeder were gained. The respondents were asked on what will be their preferred access feeder mode from the origin to the nearest LRT station. From the data, passengers were categorized in to groups with regard to the feeder mode they prefer to access the LRT station. Out of the 612 samples above mentioned, 602 samples were complete with the access travel time data. Therefore, passengers using,

- Walking and cycling
- Private cars
- Private motorcycles
- Private three-wheelers
- Taxi
- Buses

were separated into groups. Number of samples by each preferred access mode were as follow in Table 8.

Table 8: Number of Samples by Each Preferred Access Mode

Access Mode	Number of observations	Percentage of observations
Walk and Cycling	168	27.91%
Private cars	128	21.26%
Private Three wheelers	28	4.65%
Private Motor Cycles	103	17.11%
Taxi	30	4.98%
Buses	145	24.09%
Total observations	602	100%

The survey was carried out at 23 locations considering as the LRT stations. At the time of the survey, the station locations were not finalized. Therefore, those 23 locations were considered as the station locations. Those locations are,

- Kotahena
- Armour Street
- Sebatian Canal
- Keselwatta
- Fort
- World Trade Center (WTC)
- Slave Island
- Union Place
- Maradana
- Sethsiripaya
- Lumbini Temple
- Punchi Borella
- Talahena
- Cotta Road
- Welikada
- Malabe
- Rajagiriya
- Battaramulla
- Robert Gunawardana Mawatha
- Palan Thuna
- Dayawanna Lake
- Town Hall
- Borella

From the surveyed locations, it an be seen that 5 locations, namely, Kotahena, Armour street, Keselwatta, Maradana and Punchi Borella did not record any passengers as preferred as the access station. The other 18 locations recorded at least one passenger as willing to be used as the access station.
The considered data sample can also be grouped by the access station preferred by the passengers. For each station, irrespective of the access mode, the travel times can be tabulated as in Table 9.

Hereby, Sebestian will imply Sebestian Canal, WTC will imply World Trade Center and Robert G.M. will imply Robert Gunewardana Mawatha.

Table 9: Travel Time Preferences of Each Station

	Travel times (minutes)																
Stations	2	3	4	5	6	7	8	9	10	12	15	20	25	30	40	45	Total
Sebatian									1		1						2
Fort									1								1
WTC				2					1								3
Slave Island							1				1						2
Union Place									7								7
Sethsiripaya	1	1		14		1	2		34		13	8	1	2			77
Lumbini	2			13		3			28		5	4	1	1			57
Talahena	1	2		16			3		33		18	12		2	1	2	90
Cotta Road		2		10					21		4	4			1	1	43
Welikada	1	2		22	3	5	6	1	30	1	17	7				1	96
Malabe		1	1	33	1	3			39		20	6					104
Rajagiriya				1					1								2
Battaramulla				4		1			5								10
Robert G. M.				13		1			14		3						31
Palan Thuna				5	1	2	1		21	1	6	1		1			39
Dayawanna	1	1	1	10		5	1		7								26
Town Hall				3					1		1						5
Borella		1		1					2		1	1		1			7
Total	**6**	**10**	**2**	**147**	**5**	**21**	**14**	**1**	**246**	**2**	**90**	**43**	**2**	**7**	**2**	**4**	**602**

Furthermore, for each station, travel times can be further illustrated by the access mode. For Lumbini station, the travel data as travel mode vs the preferred travel times are as in Table 10.

Table 10: Travel Time Preference for Lumbini station by Different Feeder Modes

Station	**Lumbini Temple**	**2**	**5**	**7**	**10**	**15**	**20**	**25**	**30**	**Total**
Access mode	**Walk / Bicycle**	2	4		8	3	1			18
	Private Car (driver)		3	2	4					9
	Private Car (passenger)		2		2					4
	Private 3-Wheeler (driver)									
	Private 3-Wheeler (passenger)				1					1
	Motorcycle (driver)		3		4					7
	Motorcycle (passenger)			1	3	1				5
	Taxi / Hired 3-Wheeler				2					2
	Bus		1		4	1	3	1	1	11

The travel time preferences for all the stations are refereed in the Appendix A.

In a similar manner, travel time data by each access mode were identified as in Table 11 disregarding the station that the passenger will reach to access the LRT.

Table 11: Travel Time preferences for Each Feeder Mode for the Fort – Malabe Corridor

	Travel time (minutes)																
Access mode	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**12**	**15**	**20**	**25**	**30**	**40**	**45**	**Grand Total**
Walk / Bicycle	3	3		36	3	7	5	1	73	2	27	8					168
Private Car (driver)		1		37	2	7	4		34		4	2		1		1	93
Private Car (passenger)		1	2	10			1		16			4				1	35
Private 3-Wheeler (driver)				2		1			3		1				1		8
Private 3-Wheeler (passenger)				6			1		5		8						20
Motorcycle (driver)	2	4		26		2	1		28		7	1					71
Motorcycle (passenger)		1		6		2	2		14		6	1					32
Taxi / Hired 3-Wheeler	1			11		1			12		3	2					30
Bus				13		1			61		34	25	2	6	1	2	145
Grand Total	**6**	**10**	**2**	**147**	**5**	**21**	**14**	**1**	**246**	**2**	**90**	**43**	**2**	**7**	**2**	**4**	**602**

Also, the stated preference survey contained the departure time data for all access modes. From the data, departure times for bus feeder mode were specifically identified as in Table 12.

Table 12:Departure Time Preference for Bus Feeder Users

	Departure time	Number of observations
1	07:00 a.m.	103
2	11.00 a.m.	39
3	03.00 p.m.	3
		145

Speed survey denoted travel speeds at each segment from 6 A.M. to 9.50 P.M. By those values an average speed for the corridor was taken by taking the average of segment speeds for each time interval as shown in Table 6. From those corridor-wise speeds the minimum speed observed was 14.96km/h. Therefore, an average speed of 15km/h was taken as the speed of the corridor.

A data set containing all the links in the Western Province was identified which included relevant data such as the link name, distance, link category etc. These data were developed in to road network data set that can be analyzed in Arc GIS.

The GNDs in Western Province, Colombo District were considered. A data set containing the GND name, administrative details, shape characteristics, population characteristics etc. was established and modified in to a data layer that can be analyzed by Arc GIS.

Furthermore, the HH and population data of GNDs were further developed. For each GND in Colombo district, HH density was identified.

4.3 Catchment Distance and Catchment ACalculation and Analysis

Utilizing the developed data, catchment distances were analyzed. To carry out the analysis two methods were identified referencing Mendis and De Silva, 2020 (Mendis & De Silva, 2020).

1. Individual station-wise catchment distance identification
2. Corridor-wise catchment distance identification

Individual station-wise catchment identifies catchment distances for each mode separately in each station. In Corridor-wise catchment distance, a catchment distance was calculated for each mode regarding the whole corridor.

In individual station-wise catchment method, the data availability was limited. For some of the stations, data on certain modes were not available. Even though this method considers the uniqueness of stations, the error is significant due to the data limitation.

In the corridor-wise catchment method, data availability is adequate. However, it considers all the stations to be similar in geographical and socio-economic aspects.

Therefore, the results by two methods can be compared to minimize the error and thereby obtain a realistic catchment distance for each mode.

4.3.1 Individual Station-wise Catchment Distances

To identify station-wise catchment distances, for each station, travel times by passengers who are accessing the concerned station by different modes were considered. However, as a drawback it was observed that for some stations all modes were not preferred by the passengers in order to reach the station. Only some modes were preferred.

However, for the all the stations, the available data were considered and a minimum, maximum and a weighted average distance was taken for each mode at each station where the data were available. Weighted average distance was taken for each station for a certain travel mode, by taking the distances that were preferred by passengers via that mode to reach that station and weighting those distances by the number of observations for that particular distance.

e.g. For survey location A, for the feeder mode M,

Equation 1

$$Weighted\ Average(A, M) = \{\sum di(A, M) * Ni(A, M)\} / \sum N(A, M)$$

Di(A,M) = Observed travel distance i of location A, feeder mode M (i=1,2,..n)

Ni(A,M) = Number of observations for travel distance i of location A, feeder mode M

Σ N(A,M) = Total number of observations for location A, feeder mode M

E.g. For the station "Sethsiripaya", 11 observations, which were travel times in between 5minutes – 15 minutes were observed. From those observations, for the mode walking and cycling, for Sethsiripaya station, a minimum, maximum and a weighted average value can be calculated as shown in Table 13.

Table 13: Min, Max and Weighted Average Travel Distances for Walking and Cycling Mode for Sethsiripaya station

Sethsiripaya – Walk/Bicycle				
Travel time (minutes)	5	7	10	15
Travel Distance (m)	330	470	670	1000
Number of Observations	1	1	7	2
Minimum Travel Distance - 330m				
Maximum Travel Distance - 1000m				
Weighted Average Distance - 680m				

In the same manner for the mode walking and cycling, for each station, a minimum, maximum and a weighted average value can be calculated as in Table 14.

Table 14: Min, Max and Weighted Average Travel Distances for Walking and Cycling Feeder mode for All stations

Survey Location		Access (all distances in km Walking and cycling (m)		
Name	Code	min	max	W.A.
Sebatian Canal	3003	1000	1000	1000
Fort	3005	670	670	670
WTC	3006	330	670	450
Union Place	3008	670	670	670
Sethsiripaya	3010	330	1000	680
Lumbini Temple	3011	130	1000	590
Talahena	3013	200	1000	610
Cotta Road	3014	670	1000	710
Welikada	3015	330	1000	620
Malabe	3016	330	1000	610
Battaramulla	3018	670	670	670
Robert Gunawardana Mawatha	3019	330	660	550
Palan Thuna	3020	670	800	700
Dayawanna Lake	3021	200	670	420
Town Hall	3022	330	670	500
Borella	3023	200	670	440

In the same manner, for all modes, minimum, maximum and weighted average values can be calculated for each feeder mode for each station location, as shown in Table 15.

Table 15: Mini, Maxi and Weighted Average Travel Distances for Different Feeder Modes

Survey Location		Access (all distances in km)																	
		Walking and cyclin			Private Car (km)			Private Threewhee			Private Motorcycl			Taxi (km)			Bus (km)		
Name	Code	min	max	W.A.	min	max	W.A.	min	max	W.A.	min	max	W.A.	min	max	W.A.	min	max	W.A.
Kotahena	3001																		
Armour Street	3002																		
Sebatian Canal	3003	15	1000	1000															
Keselwatta	3004																		
Fort	3005	10	670	670															
WTC	3006	7	330	670															
Slave Island	3007										2	2	2				3	3	3
Union Place	3008	10	670	670							3	3	3	3	3	3	2	2	2
Maradana	3009																		
Sethsiripaya	3010	10	330	1000	1	8	3				1	5	2	1	1	1	1	5	2
Lumbini Temple	3011	9	130	1330	1	3	2	3	3	3	1	4	2	3	3	3	1	5	3
Punchi Borella	3012																		
Talahena	3013	10	200	1330	1	3	3	3	3	3	1	4	3				2	7	3
Cotta Road	3014	12	670	1330	1	1	1	10	10	10	1	5	2	1	4	2	1	8	3
Welikada	3015	10	330	1330	1	5	2	1	4	3	1	4	2	1	5	2	2	8	3
Malabe	3016	9	330	1330	1	5	2	1	4	3	1	4	2	3	4	3	1	3	2
Rajagiriya	3017				1	3	2												
Battaramulla	3018	10	670	670	1	3	2	3	3	3	3	3	3						
Robert Gunawardana	3019	8	330	660	1	4	2	1	3	2	1	4	2	1	1	1	2	3	2
Palan Thuna	3020	11	670	800	1	3	2				1	4	3	1	5	3	1	5	2
Dayawanna Lake	3021	6	200	670	1	3	2	3	3	3	1	2	1				2	2	2
Town Hall	3022	8	330	670													1	3	1
Borella	3023	7	200	670	3	3	3										1	5	3

From the above calculated weighted average distances for each station, an average value for a certain mode (M) representing all the stations was calculated following the equation.

Equation 2

$Catchment\ Distance(M) = \{\sum(Weighted\ avergae(A, M) * N(A, M))\}/$ N(M)

A = station number (A= 1,2,…,15)

$N_{A,M}$ = Number of observations for station A for mode M

N_M = Total number of observations for mode M

E.g. for walking and cycling mode, the weighted average values identified for each station and the number of observations are shown in Table 16. The weighted average values and the number of observations a each station for all the modes are shown in Table 16.

Table 16: Catchment Distance value for Walking and Cycling Mode for each Station

Name	Walking and cycling (m)	
	Weighted Average	*Number of Observations (N)*
Fort	670	1
Union Place	670	1
Sethsiripaya	680	11
Lumbini Temple	590	18
Talahena	610	15
Cotta Road	710	18
Welikada	620	36
Malabe	610	29
Battaramulla	670	1
Robert Gunawardana Mawatha	550	8
Palan Thuna	700	4
Town Hall	500	2
Borella	440	2
Total		146

Catchment distance = [Σ (Weighted Average * N)]/ 146

Thereby the catchment values for the modes were observed to be as in Table 17.

Table 17: Catchment Distances for Each Mode

Feeder Mode	Catchment Distance
Walk and Cycling	640m
Private cars	2059m
Private Three wheelers	2548m
Private Motor Cycles	2112m
Taxi	2242m
Buses	2384m

4.3.2 Generic Corridor-wise Catchment Distance

To identify a catchment distance for a certain mode in the aspect of the generic corridor, the data set representing the whole corridor was utilized. The access station that the passenger will access the LRT was disregarded. From the data set, for a certain access mode, the frequencies of different travel distances being preferred for the purpose of reaching the access station were identified. Thereby, the behavior of passenger preference of travel distances with respect to the accumulation of travel distance was investigated.

For an example, for the mode walking and cycling, the stated travel distances can be regarded in classes of 100m and the frequency of a certain class occurring can be graphed.

Furthermore, cumulation of frequency can be observed relative to the cumulation of travel distance to the access station.

The frequency variation and the cumulative frequency variation is visualized for all access modes in Figure 6 to Figure 11.Figure 7

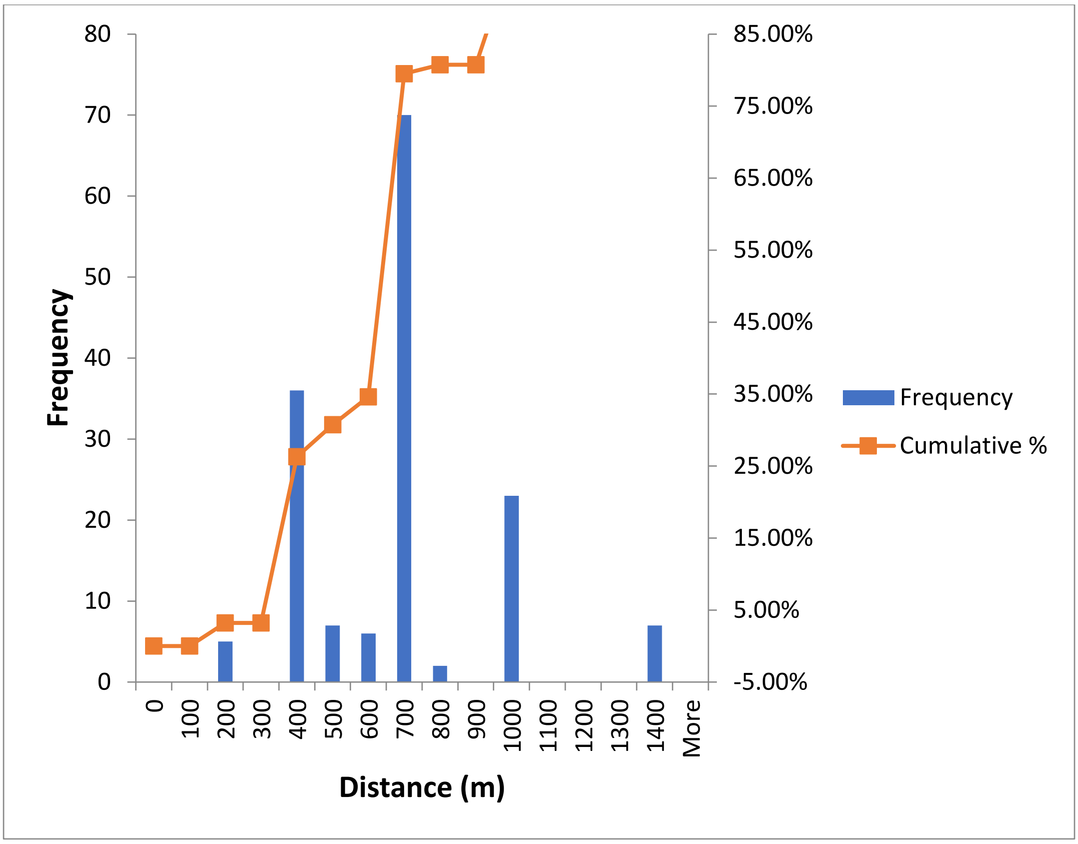


Figure 6: Walking and Cycling Histogram

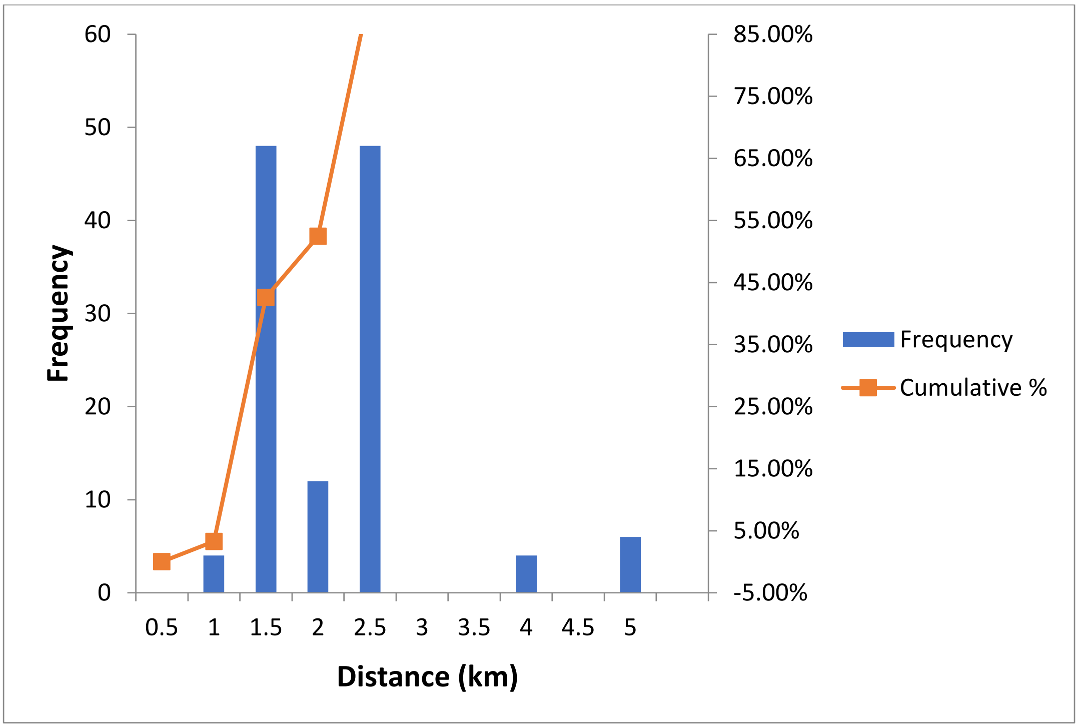


Figure 7:Cars Mode Histogram

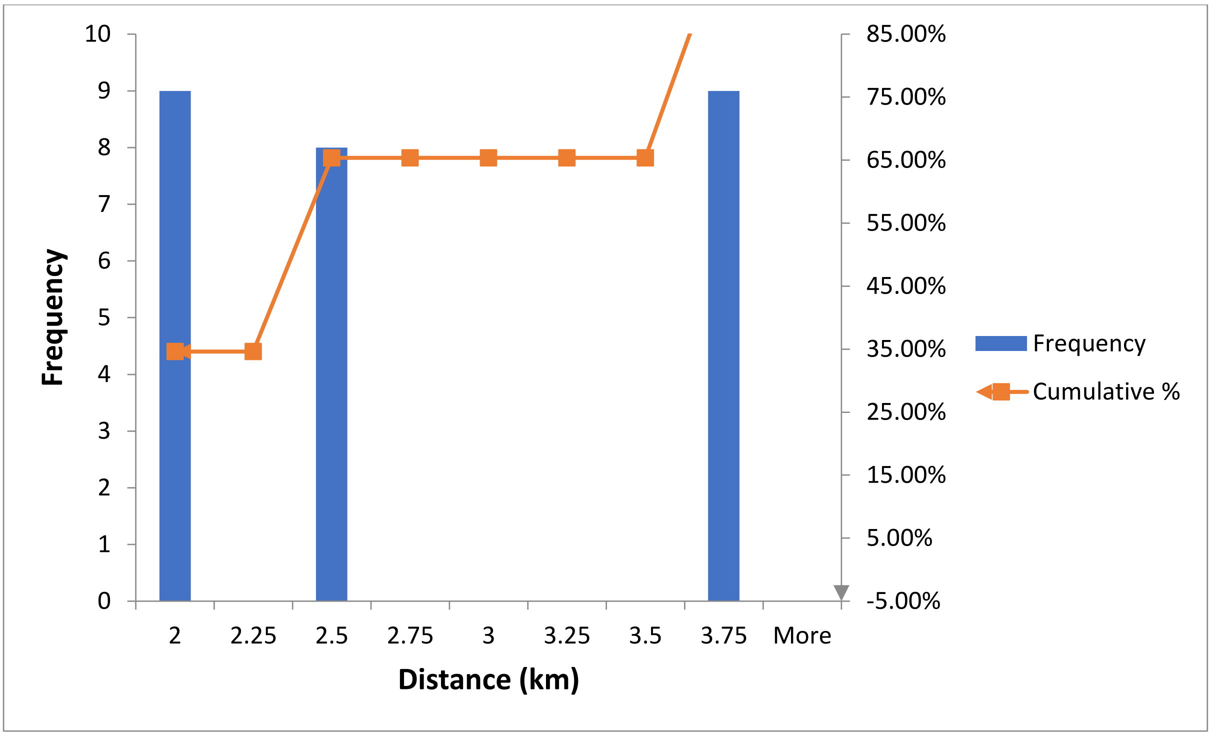


Figure 8:Three-wheelers Mode Histogram

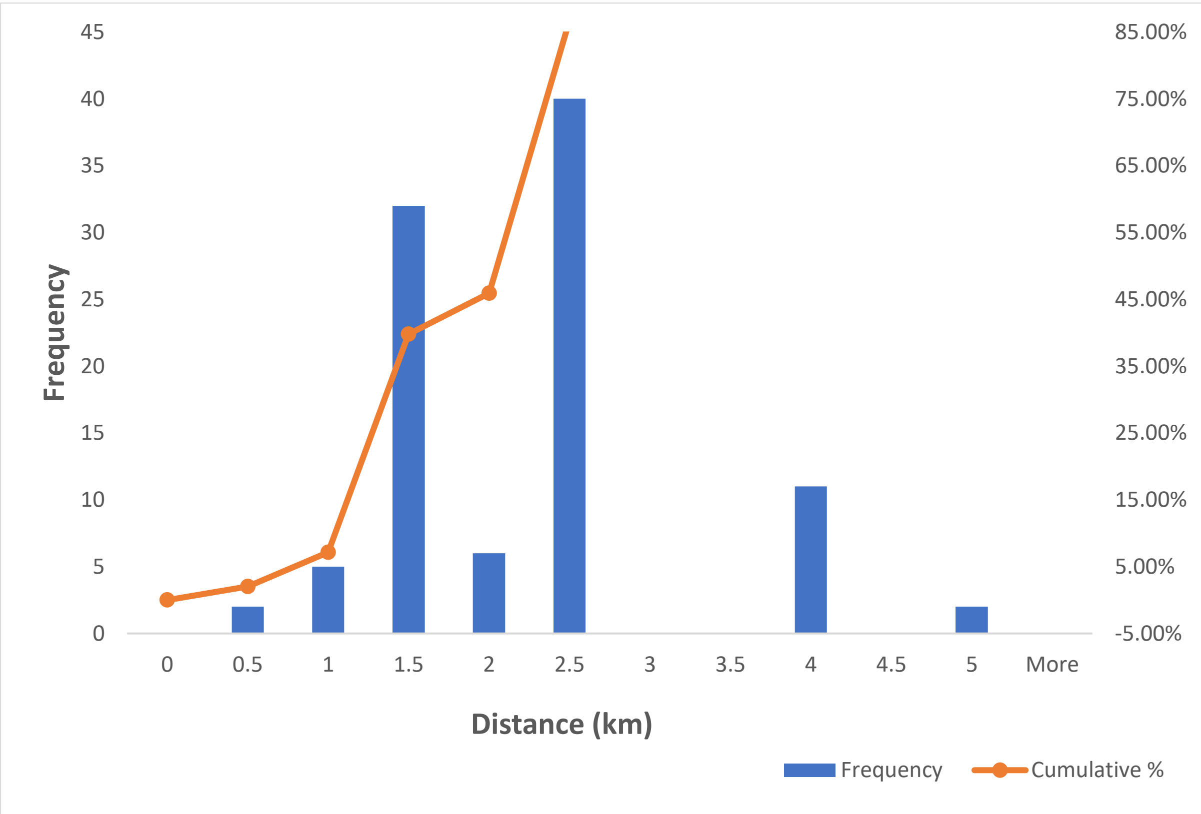


Figure 9:Motorcycles Mode Histogram

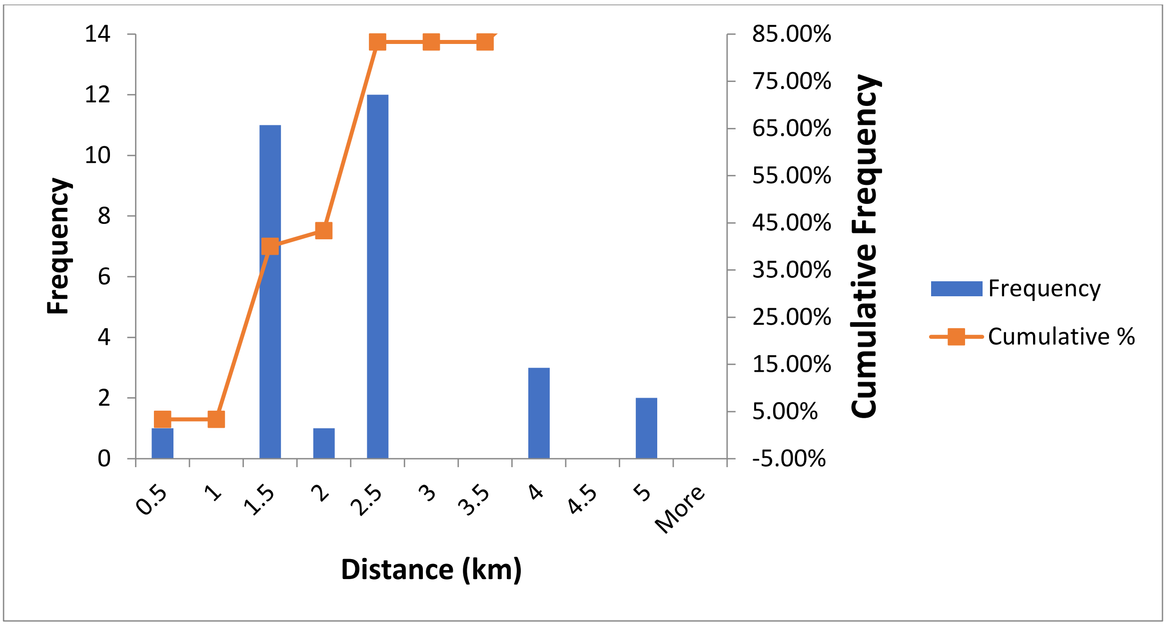


Figure 10:Taxi Mode Histogram

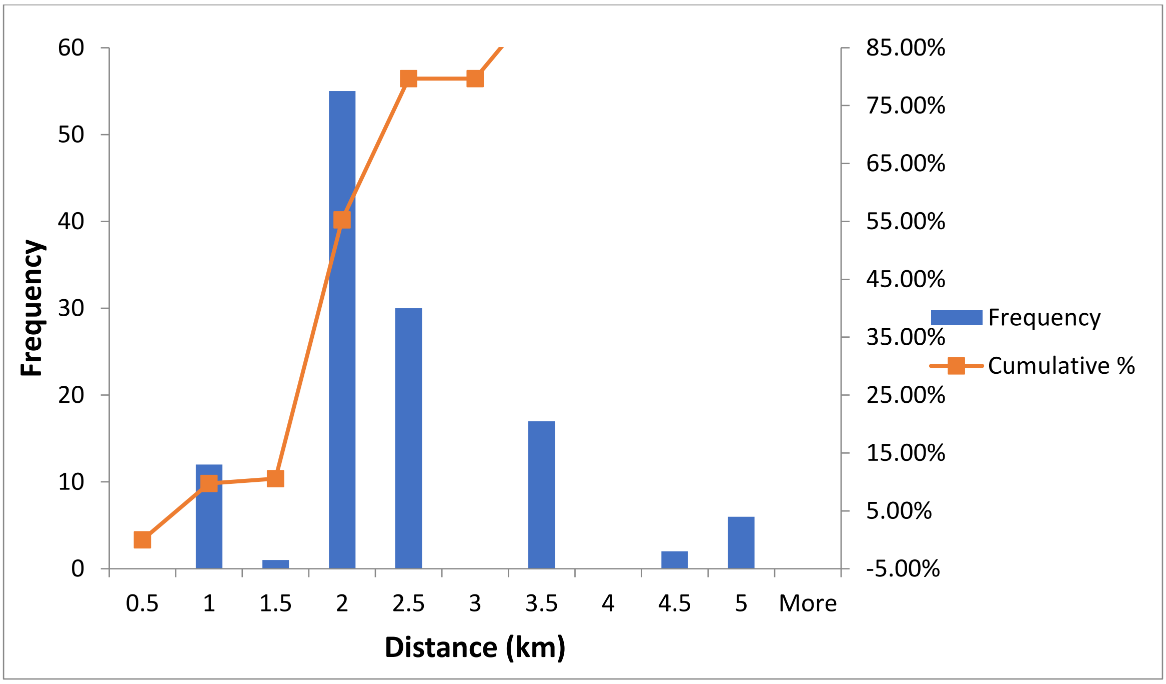


Figure 11:Bus Mode Histogram

A gradual increase of frequency in travel distance preferences can be observed along the accumulation of travel distance. This upward trend continues up to a point and then the frequency continues to drop with the increase of the travel distance.

This trend can be understood to be practical as the number of people that are willing to travel only a very short distance is limited, therefore the initial lower starting point. In mid-range distance values, peaks of frequency can be seen. In the long travel distance values again a decline can be seen which may be due to perception of avoiding travelling for a long distance.

When considering all the modes, similar trend can be seen in all modes except the three-wheeler mode.

The maximum distance recorded as preferred for each mode to access the LRT can be observed. However, taking this value as the catchment distance may be over-estimating the catchment. Therefore, referring the literature such as Ann et al. (2019), (Ann, Jiang, & Yamamoto, Influence Area of Transit-Oriented Development for Individual Delhi Metro Stations Considering Multimodal Accessibility, 2019), Ann et al. (2019), (Ann , Jiang, Mothafer, & Yamamoto, 2019), Wakenshaw and Bunn, (2015), (Wakenshaw & Bunn, 2015) etc., 85th percentile of cumulative frequency was taken as the catchment distance for a certain mode shown in Table 18.

Table 18: 85th Percentile Catchment Distances for Each Feeder Mode

Feeder Mode	**Catchment Distance 85% cumulative frequency**	**Variation from observation 1**
Walk and Cycling	806m	158m
Private cars	2413m	354m
Private Three wheelers	3641m	1093m
Private Motor Cycles	2478m	366m
Taxi	2523m	281m
Buses	3192m	808m

4.3.3 Comparison of Catchment Distance Calculation Methods

To determine the catchment distances for each mode, the above calculated catchment distance values by the two methods were compared. The objective of following two scenarios to calculate catchment distance was to eliminate the error and obtain a more accurate value. The first observation considers catchment distances for each mode individually for each station where travel distances are weighted by the frequency they are preferred. Therefore, takes the geographical, physical and socio-economical differences throughout the stations in to the account. Second scenario which is based on the cumulative frequency of a travel distances being preferred with the accumulation of travel distance considers the perspective of the complete corridor where the corridor is considered to be consistent in characteristics throughout.

The first observation is strengthened by the facts that it considers the frequency of travel distances being preferred and the inclusion of station uniqueness. However, in this as shown in Table 15, for each station not all modes are recorded to be preferred by the passengers. Therefore, for some stations, the catchment distance for some modes, cannot be calculated due to the lack of data availability. In observation 2, the data availability was sufficient with each mode including at least 26 samples for the mode. However, the second observation does not take the individuality of the stations in to account.

In comparison between the results by observation 1 and 2 it can be seen that the results tally with a maximum difference of 336m for modes walking and cycling, car, motor cycles and taxi as seen in Table 19.

Table 19: catchment Distance Variations by Two Observations

Feeder Mode	Catchment Distance 85% cumulative frequency	Variation from observation 1
Walk and Cycling	806m	158m
Private cars	2413m	354m
Private Three wheelers	3641m	1093m
Private Motor Cycles	2478m	366m
Taxi	2523m	281m
Buses	3192m	808m

In the modes three-wheelers and buses significant differences between results by observation 1 and observation 2 can be seen.

In mode three-wheelers, it can be observed that the sample size available is limited which is only 26 samples for all station access. Also, the distribution of the sample data is visibly different to the other modes. In other modes such as walking and cycling, the initial smaller travel distances were preferred infrequently and then the frequency of preference increases with the travel distance up to a point and then shows a reduction of frequency of preference with travel distance accumulation as shown in Figure 8 shows the mode three-wheeler, where this trend is not to be seen.

Therefore, catchment distances for three-wheelers in both scenarios were taken as deviations. Also, it can be seen in observation 2, catchment distance for the three-wheeler mode deviates majorly from other private feeder modes again possibly due to previously mentioned facts.

Regarding the bus feeder mode, again there is a significant difference between the values identified in observation 1 and 2. Reason for this can be that in bus mode, the catchment distance with the highest frequency of occurring (2km), does not tally with the catchment distance where 85th percentile of cumulative frequency occurs (3.2 km). In other modes such as private cars and motor cycles these two scenarios occur at the same catchment distance.

4.3.4 Catchment distance determination

Observation 1 was carried out considering the possible differences of population density, land use patterns and geographical features at each station. However, the sample size for each station was limited and in some stations for a certain mode samples were not available. In observation 2, the generic scenario was considered and the sample size was sufficient and covered all the modes. Also, as all the LRT stations were situated in urban areas with the same ranged population density and land use patterns, the catchment distances were assumed not to be unique to individual stations. Therefore, as the catchment distances, the results obtained in the observation 2 were employed.

It can be observed private motorized vehicles and taxi other than three-wheelers consists of catchment distances varying in the range of 2400m- 2550m. Therefore, all private vehicles and taxi were taken as one category. Considering all the observations in the sample consists of rounded numbers, the identified catchment distances were also rounded off. Therefore, the catchment distances taken in to consideration is as in the Table 20.

Table 20: catchment Distance Determined for Feeder Modes

Mode	Catchment Distance
Walking and Cycling	800m
Private vehicles and taxi	2500m
Buses	3200m

4.3.5 Catchment Area Analysis

Two types of approaches can be followed to identify the physical catchment boundary. First approach is the circular buffer approach and the second is the service area approach.

In Circular buffer approach, the Euclidian distances from a station is taken (Andersen & Landex, 2009). The circular buffers can be identified using GIS. The output circular catchment areas are as shown in Figure 12 to Figure 14.

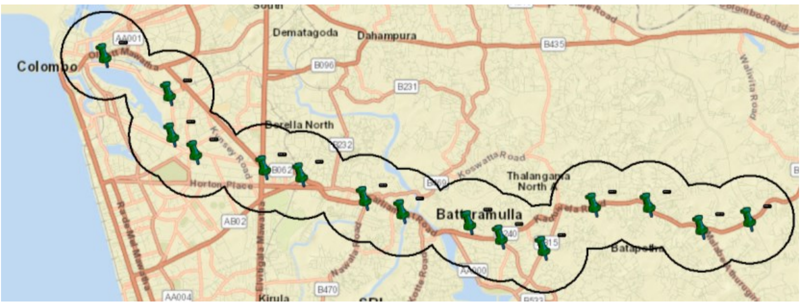


Figure 12: Circular buffer for Walking and Cycling Mode(800m Catchment Distance)

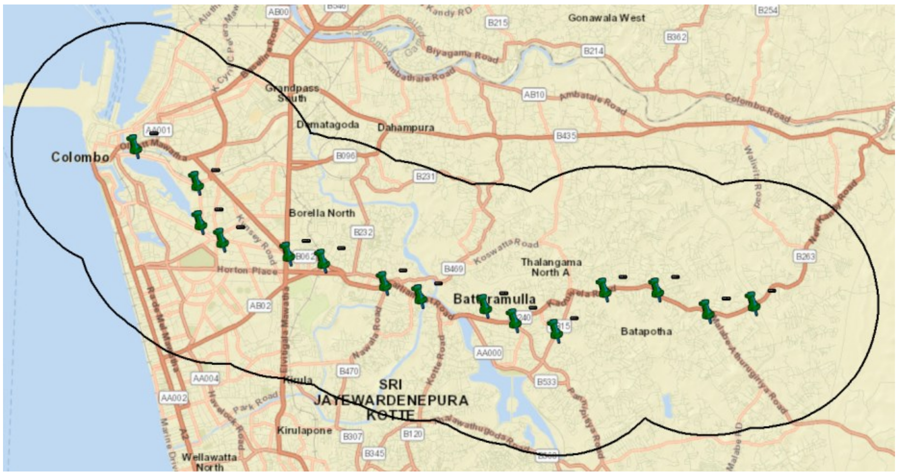


Figure 13: Circular buffer for Private and Taxi Modes(2500m Catchment Distance)

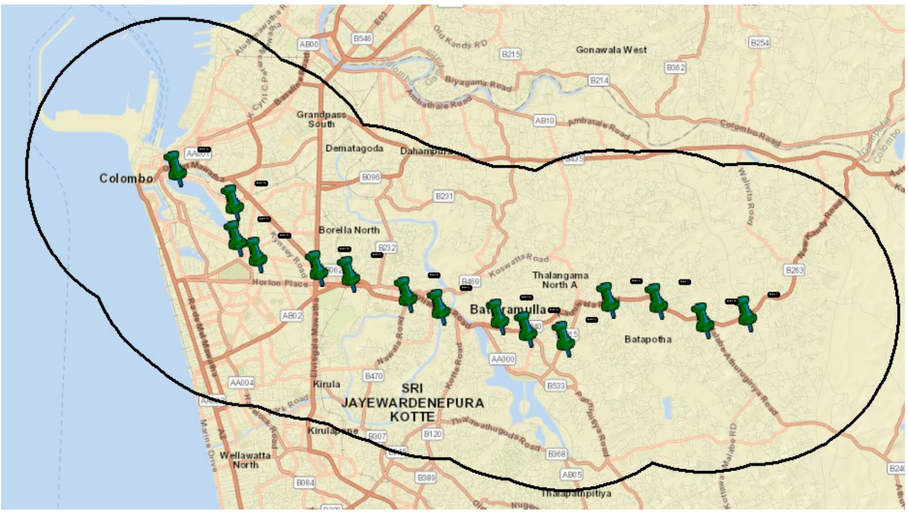


Figure 14: Circular buffer for Buses Mode (3200m Catchment Distance)

In the Service area approach the travel distance by the road network is taken. Following the service area approach, the geographical catchment area for different modes were recognized as follows in Figure 15- Figure 17, by using Geographical Information System.

Figure 15: Service Area for Walking and Cycling Mode (800m catchment Distance)

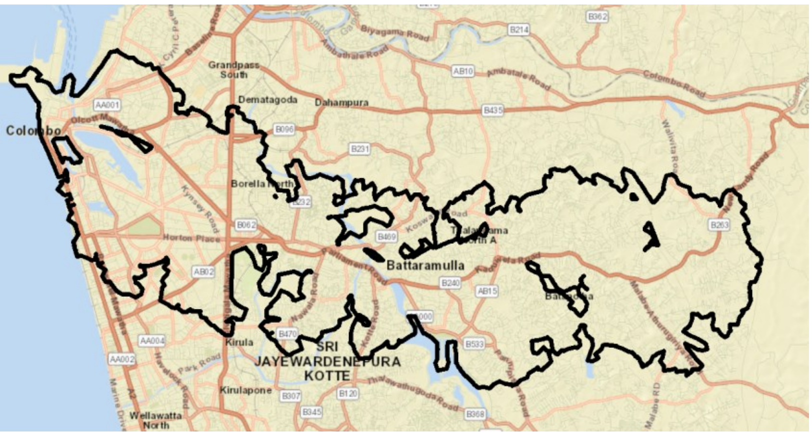


Figure 16: Service Area for Private and taxi Modes (2500m catchment Distance)

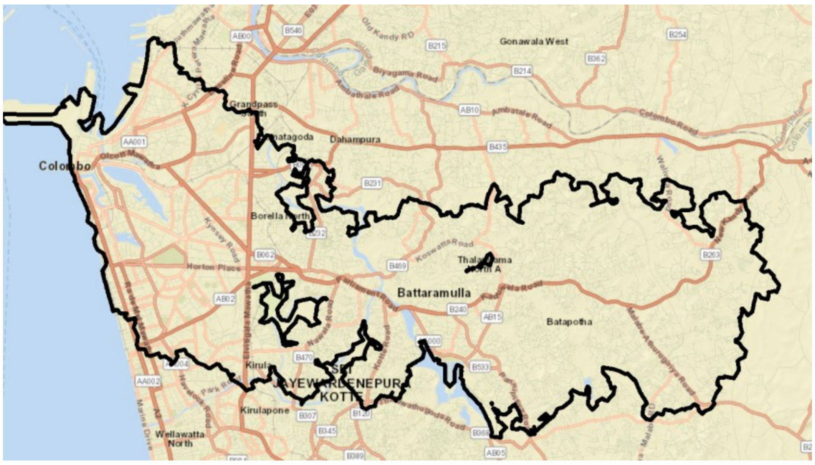


Figure 17: Service Area for Buses Mode (3200m catchment Distance)

In order to identify the more accurate catchment area, the two approaches were compared. It can be seen that the catchment area details that can be obtained by circular buffer approach are limited as the variation of catchment area with geographical features such as limitations of road network connection, buildings and water bodies presence are not observed. The areas that are not disconnected from a certain station due to a water body or an expressway can be seen as a part of the catchment in circular buffer method. This can be specially observed when considering that in the circular catchment area for private vehicles, taxi modes and buses visualizing the coast and the sea area as part of the catchment as seen in Figure 18. These limitations are mitigated in Service Area Approach.

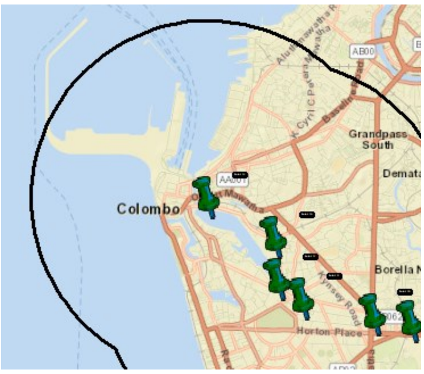


Figure 18: Sea and Coastal area as part of the Catchment Area

Comparing the Circular area approach the Service area approach for the same mode, it can be seen that circular area approach catchment buffer indicates some inaccessible areas such as canals and the areas that cannot be accessed due to the limitation of the street network. This can be clearly seen in Fort and Maradana stations as shown in Figure 19. It can be seen that the circular buffer approach is clearly over-estimating the catchment area when compared with the service area approach.

Figure 19: In-accessible areas included in the catchment

Therefore, it can be deemed that the catchment area given by service area approach is more realistic compared to the circular buffer approach. By service area approach, detailed analysis of the catchment area can be carried out. The comparison of catchment areas by two approaches for different modes are shown in the Table 21.

Table 21: Catchment Areas by Two Approaches

Mode	**Catchment area (km^2)**	
	Circular Buffer Approach	**Service Area Approach**
Walking and Cycling	24.45 km^2	13.92 km^2
Private vehicles and Taxi	89.24 km^2	51.62 km^2
Buses	125.78 km^2	74.99 km^2

As seen in the comparison between the catchment areas by the two approaches, Circular Buffer and Service Area Buffer, it can be identified that the Service area buffer approach is more suitable for the catchment area analysis as the area is identified with the consideration of physical barriers such as water bodies and road network discontinuation. Furthermore, the observations of the survey, upon which the conclusions were made, were observed as distance by the road network instead of aerial distance. Therefore, the service area approach is utilized in catchment area identification.

Thereby, the catchment areas for each feeder mode were visualized using Arc GIS. From the visualization, the catchment areas are shown in Figure 20, 21 and 22.

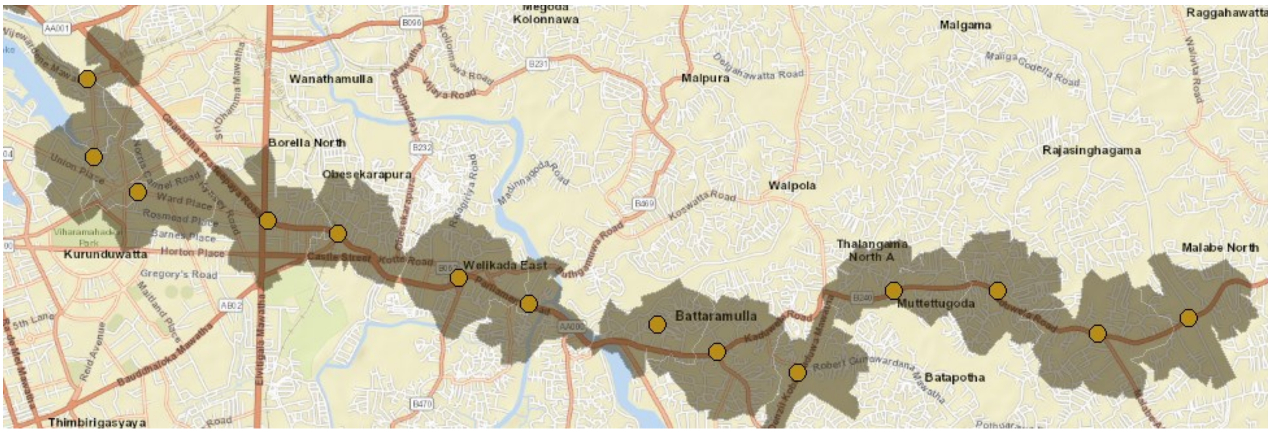


Figure 20: Catchment area of Walking and Cycling Mode

Catchment area is measured to be 13.92 km^2.

Figure 21: Catchment Area of Private Veh and Taxi

Catchment area is measured to be 51.62 km^2.

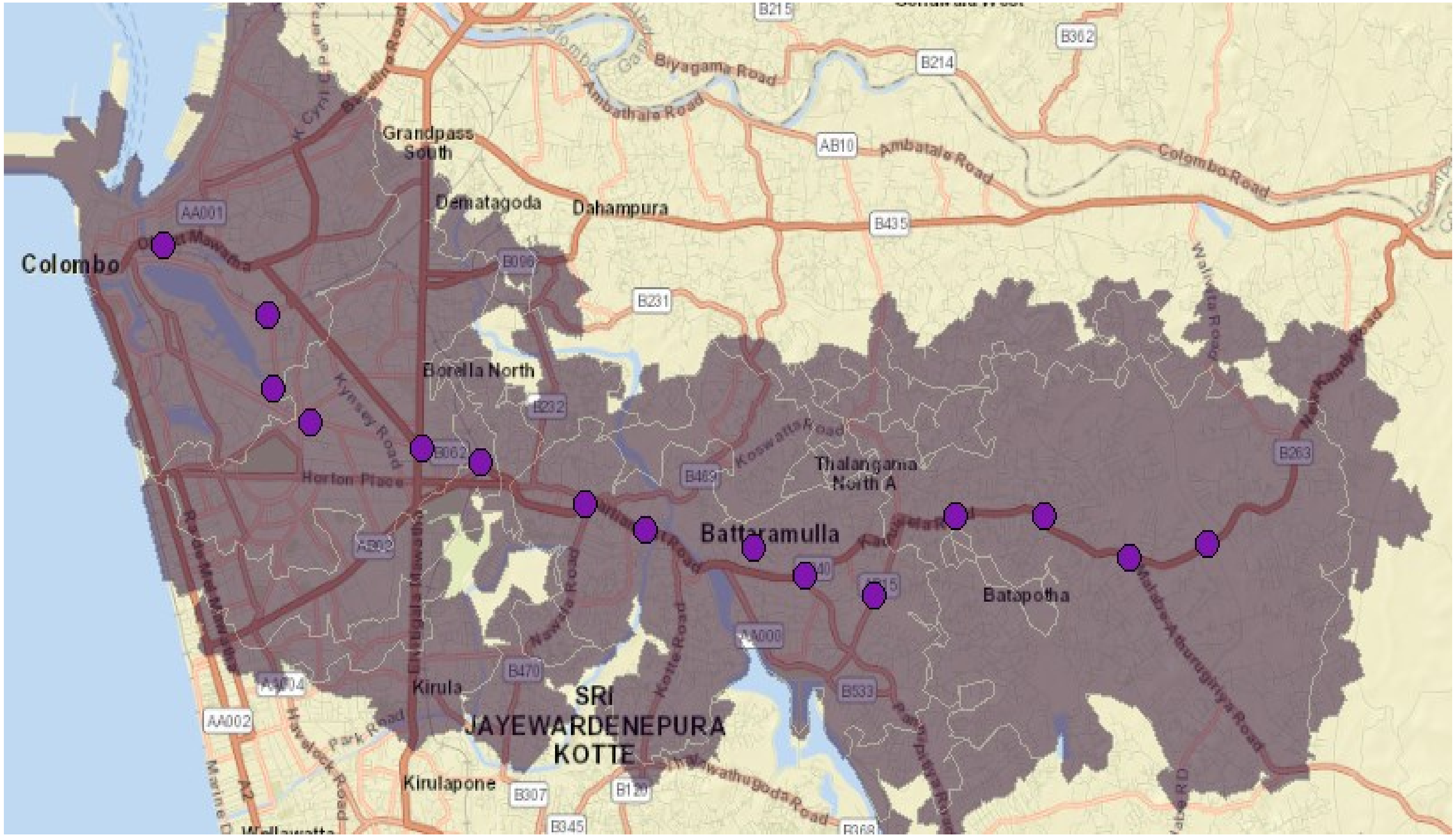


Figure 22: Catchment Area of Bus Mode

Catchment area is measured to be 74.99 km^2

By the above calculations, it can be concluded that the catchment area for walking and cycling mode is 13.92 km^2, catchment area for private vehicle mode is 51.62 km^2 and catchment area for bus mode is 74.99 km^2 which are geographically shown. The catchment areas that were calculated and visualized can be further analyzed.

The catchment area for walking and cycling mode can be seen to be limited due to water bodies and structures. As an example, in Maradana station the catchment is seen limited due to Bere Lake canal system and the Maradana railway yard. The streets and paths discontinue and therefore the catchment area is limited.

The catchment area can be suggested to be improved by implementing connections such as foot paths and foot bridges over the water bodies and enclosed areas that are barricading the catchment area. Figure 23 shows how a footbridge connection across Beire Lake can eliminates the limitation due to the water body and hence increase the catchment area. Increase of catchment area is 0.06km^2 which is a 10.3% increase.

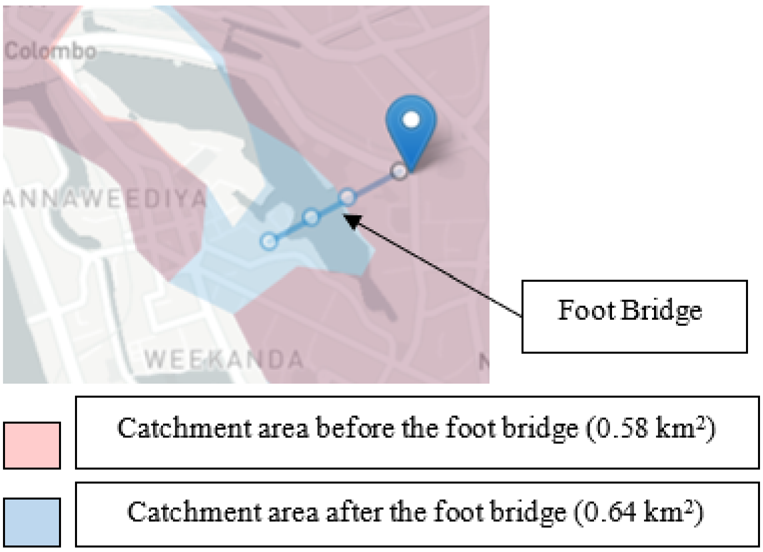


Figure 23: Increase of Catchment Area by the Implementation of Foot Bridge at Fort

Private vehicle catchment can be observed to be limited due to water bodies and large structures in the corridor. However, the implementation of new road networks to make the inaccessible areas accessible, might not be practical with the nature of development in Fort – Malabe corridor.

For the public transport mode bus, the geographical catchment area can be identified as 74.99 km^2 which was calculated by considering the 3.3km catchment distance. This catchment area is the largest of feeder modes. Therefore, it can be assumed that there is a high demand for bus feeder.

4.4 Assessing the Modal Share of Bus Feeder

The modal share was identified initially by data and it is shown in Table 22.

Table 22: Feeder Mode Modal Share

Access Mode	Number of observations	Percentage of observations
Walk and Cycling	168	27.91%
Private cars	128	21.26%
Private Three wheelers	28	4.65%
Private Motor Cycles	103	17.11%
Taxi	30	4.98%
Buses	145	24.09%
Total observations	602	100%

It can be identified that the bus feeder mode accounts for 24.09% of the feeder preference which is a significant percentage. Also, in catchment area calculation, it was observed that the catchment area for the bus feeder was 74.99km^2 which is again a significant area compared to other feeder mode catchment areas.

Hence, the bus feeder network is of great importance for this corridor and for the success of the LRT in this corridor as the impact by the bus feeder is significant as it is the only public feeder mode available in the corridor.

4.5 Analyzing Bus Catchment Area and Accessibility by Present Bus Network

However, even though passengers in this catchment area prefers to take the bus mode, it can be observed that in the identified catchment area of the bus feeder, bus services are operating mostly in the major routes and some of the areas of the geographical catchment does not have of any operating bus route currently. Therefore, the bus catchment is not only limited by the catchment distance and physical barriers but also by the availability of bus routes.

To identify the limitation by the availability of bus routes, the existing bus network is required to be identified, in this case the data on bus routes operating in the catchment boundary were collected.

To identify the existing bus routes that are operating in the physical catchment area, surveys were carried out. By the survey and data from Western Province Transport Authority, 102 routes operating in the identified bus catchment area were recognized. In those bus routes, for each route, the path of the bus route, the stop locations that are applicable, the frequency were identified. Figure 24 visualizes the bus routes that were identified to be operated in the catchment area. 106 bus routes were identified to operating. Most of the bus routes were operating in the Fort – Malabe corridor itself fully or partially while some of the others connected the residential areas with the LRT trace. However, some of the routes were observed to be parallel to the LRT alignment.

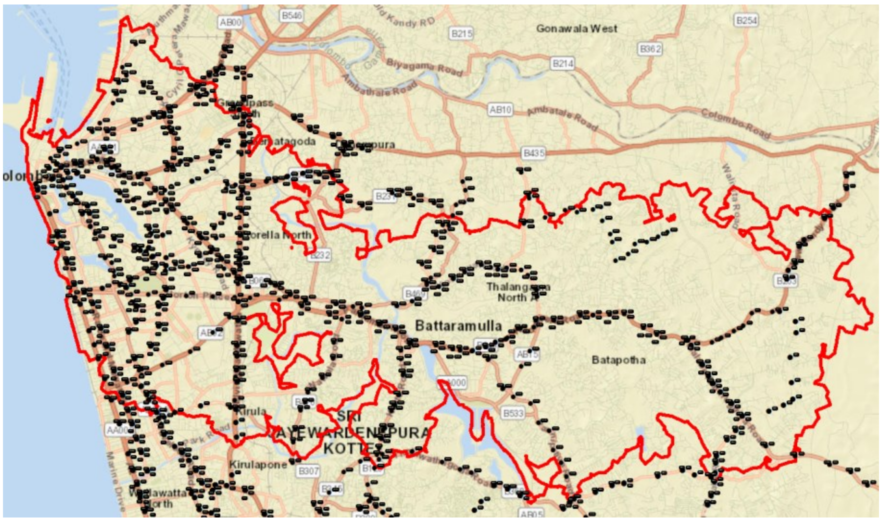


Figure 24: Bus Route Operating Paths in the Fort- Malabe Corridor

Using the data collected, a Geo Transit Feeder System (GTFS) which is a type of data base, which has a pre-determined structure was developed for further reference.

Conveyal is a web-based analysis tool used in accessibility analysis. The Conveyal analysis which is used globally can be used to measure the accessibility indicators and visualize the accessibility. Thereby, Conveyal analysis was utilized to recognize the accessibility that is enabled by the present bus network.

Using the Conveyal analysis, the area that is accessible per each station was recognized. In this feat, the walking distance of 400m was considered to be the maximum distance that a passenger is willing to travel to board a bus to reach the nearest LRT station. The time limit by the bus mode was taken to be 20 minutes, which was the observed value by data, that the passengers were willing to travel by bus to reach an LRT station.

After obtaining area accessible for each station by the current bus network, the areas identified were visualized in Arc GIS software.

The effect on catchment area by the available bus network was visualized as in Figure 25. The catchment area that the passengers are willing to travel from to reach the nearest LRT by bus feeder is currently ill supplied by the present bus network as seen in below Figure 25.

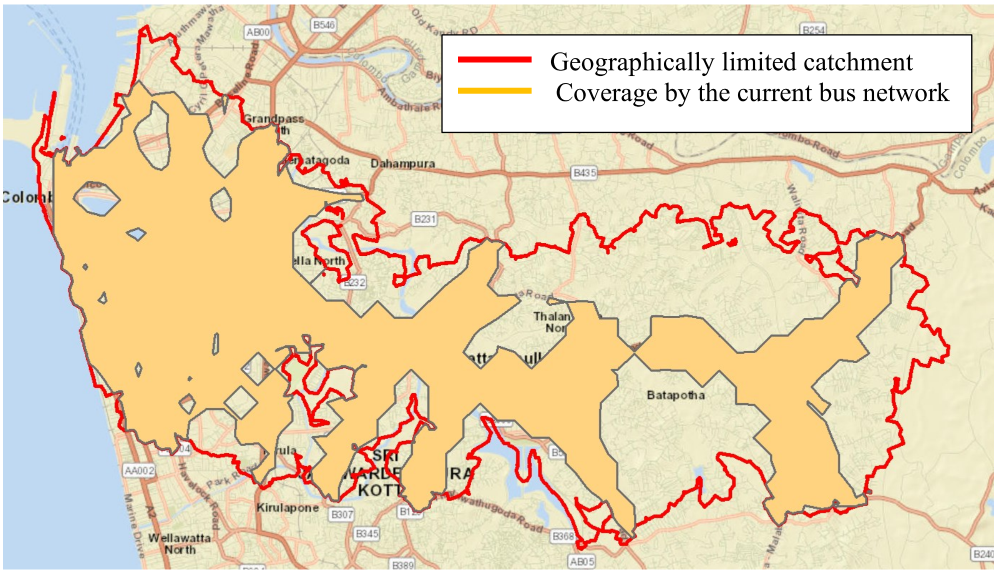


Figure 25: Comparison Between Catchment of Bus Mode and the Coverage

Even though the catchment area by service area approach consists of an area of 75km^2, the actual catchment area of Fort- Malabe LRT for the feeder mode buses, is limited to 40.28 km^2 due to the lack of accessibility by bus routes.

4.6 Applying Bus Feeder Design Method strategies

As per the previous observation, it can be seen that the bus catchment is not optimally supplied by the current bus network. Therefore, to sufficiently supply to the demand of a bus feeder, a proper bus feeder system is required.

In designing a bus network for the identified catchment of 74.99 km^2, the objective was determined as achieving the highest possible coverage by the bus network, ideally achieving 100% coverage of the catchment area so that all the passengers in the catchment area is provided with accessibility to the nearest LRT. To achieve this objective, one method that would be investigated was modifying the existing bus network, so that the area that are currently not supplied by the existing bus network will have coverage from bus mode. However, alternatively, designing a new bus network, without considering the existing bus network is also a plausible method.

In the current bus network, there are several bus routes, that have parallel paths to Fort-Malabe LRT. However, in the condition where the LRT will be operating in Fort- Malabe corridor, the parallel bus routes tend to lose the demand. Also, parallel routes will be competitive with the LRT, reducing the effectiveness of the LRT. As the LRT will be providing the backbone connection in the corridor, the bus network's major objective requires to supply the LRT by connecting residential areas with LRT stations. Hence designing a bus feeder network, disregarding the existing one, is a strong requirement.

However, in the practical scenario, implementation of a new bus network differing from the existing one might affect the social aspects of the residents that are willing to access LRT by bus mode.

Hence, in designing bus network, both methods mentioned below are followed and then compared to identify the most effective method that has the highest coverage.

- Design Method 1 - Modifying the existing regular bus network
- Design Method 2 - Designing a new bus network disregarding the existing network

4.6.1 Design Method 1 - Existing Bus Network Modification

Modification of the existing regular bus route was the first design method to be followed. In this method, the feeder system will operate as a part of the regular network. The bus network operating in the catchment will consist of regular bus routes and additional dedicated feeder bus routes both. A portion of the demand, for trips to access the LRT from the catchment, will be satisfied by the regular bus network which will be the same as the present existing bus network. The objective in the method is to identify the areas that are currently not covered by the existing network and provide coverage to those areas by new bus routes in the constraint of bus routes being implemented in the shortest possible path, in links that were identified to have suitable road class. Several steps were identified to be followed.

1. Identifying the catchment area and GNDs not supplied by the existing bus routes
2. Identifying the centroids of GNDs considering only the uncovered shape area
3. Identifying the shortest path links connecting the GNDs to the nearest LRT station
4. Implementing an individual feeder bus route in each identified link above

4.6.1.1 Identifying the Catchment Areas not Supplied by the Existing Bus Routes

In order to modify the existing bus network with new feeder routes, using the data collected on existing bus routes, the catchment area that is covered by the bus routes and the catchment area that is not covered by the existing bus routes were identified and visualized as in Figure 26.

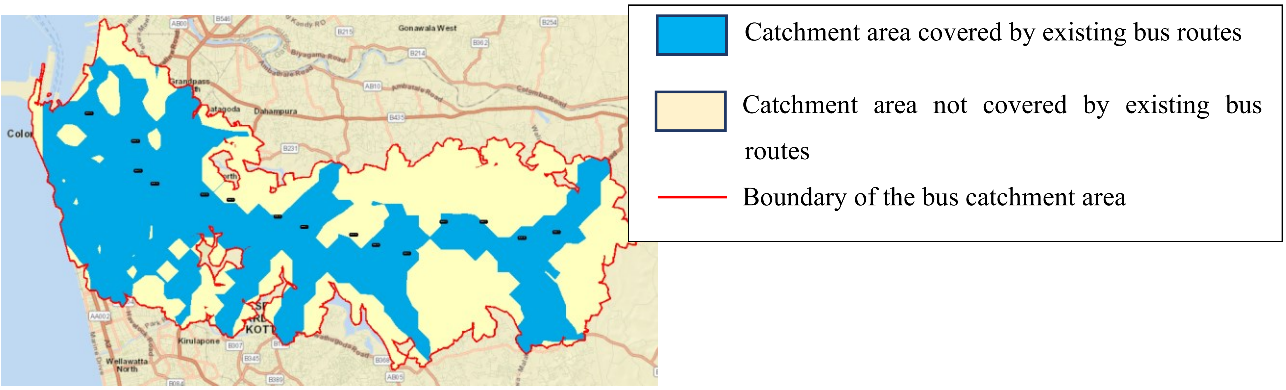


Figure 26: Catchment Coverage by Existing Bus Network

By the Geographic Information System (GIS), the GNDs that are not supplied by the current bus network were identified. The visualization is shown in Figure 27. 115 GNDs were identified to be having non or partial coverage from the existing bus network.

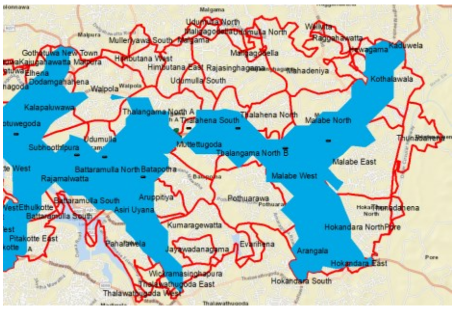


Figure 27: GNDs not suplied with the Current Bus Network

4.6.1.2 Identifying the Centroids of GNDs Considering Only the Uncovered Shape Area

The centroids that were previously identified for each GND considers the shape area of the whole GND bounded by the geographical catchment area. However, in modifying the bus network, as the objective was to supply for the uncovered area, the shape area that is uncovered by the existing bus network, in each GND was considered as relevant. Therefore, centroids of each GND uncovered shape area were identified and visualized using Arc GIS as shown in

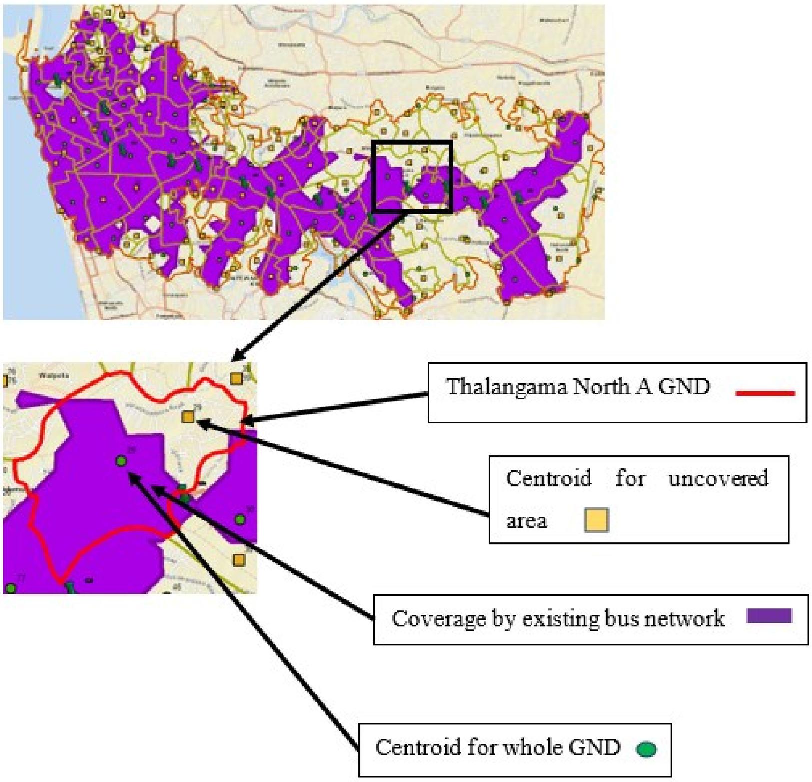


Figure 28: Centroid Location

4.6.1.3 Identifying the Shortest Path Links Connecting the GNDs to the Nearest LRT Station

To access the LRT, a passenger was assumed to be choosing the shortest possible path. Inside the identified catchment for bus mode, for the 115 GNDs that need improved coverage, a route network that connects each GND with the nearest LRT station was identified. In this case centroid identified for the uncovered area of GND was considered to account for the GND shape area.

Thereby, using the closest facility option of Network Analyst function of Arc GIS software, shortest paths for each GND centroid connecting with the nearest LRT station were identified as shown in Figure 29. In this feat, the hierarchy of links was considered. Hierarchy of links were as Primary, secondary, tertiary and residential. Therefore, the shortest paths were aligned in the upper hierarchy links first and lower hierarchy links such as residential links were only used to maintain the connection with the centroid, as the some of the centroids were only accessible by residential links.

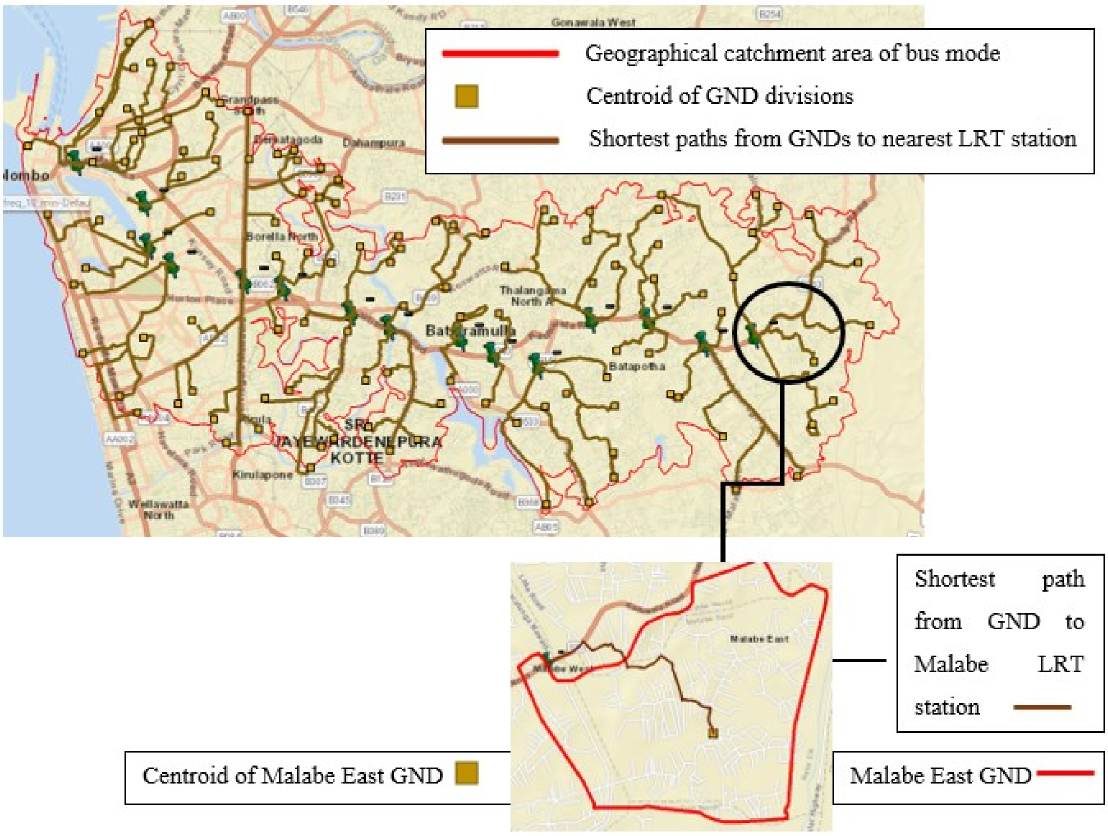


Figure 29: Shortest Path Identification

4.6.1.4 Implementing an Individual Feeder Bus Route in Each Identified Link Above

After identifying the shortest path connecting each GND with the nearest LRT stations, an individual bus route was assigned to each of these paths, to analyze the coverage offered by these routes.

Inside the considered catchment area, the existing road network consists of several types of links such as motorways, primary links, secondary links, tertiary links, residential links etc. Therefore, the shortest path route may align via numerous types of links. However, not all these links can accommodate a bus network due to the limitation in the width. Therefore, for the bus network, only primary, secondary and tertiary links (A, B, C and D classes) were considered. The identified links are as shown in Figure 30.

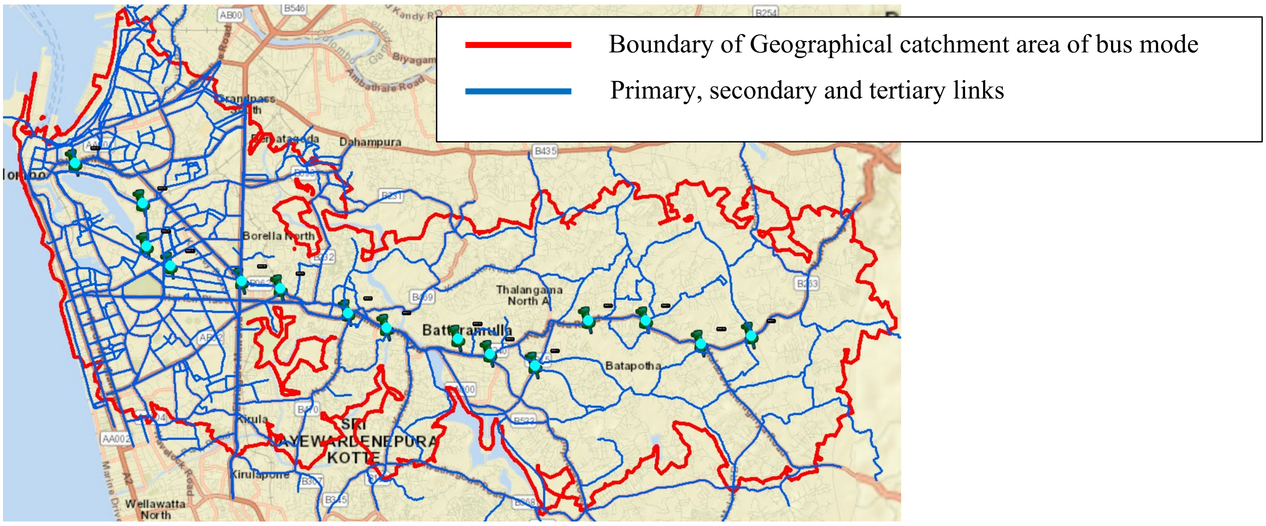


Figure 30: Eligible Links

Therefore, it was observed that, even though the shortest paths connecting the 115 GNDs were identified, all those paths cannot be assigned with a bus route. For an example, Figure 31 shows how some of the shortest path links are not eligible partially for bus routes due to the links being residential.

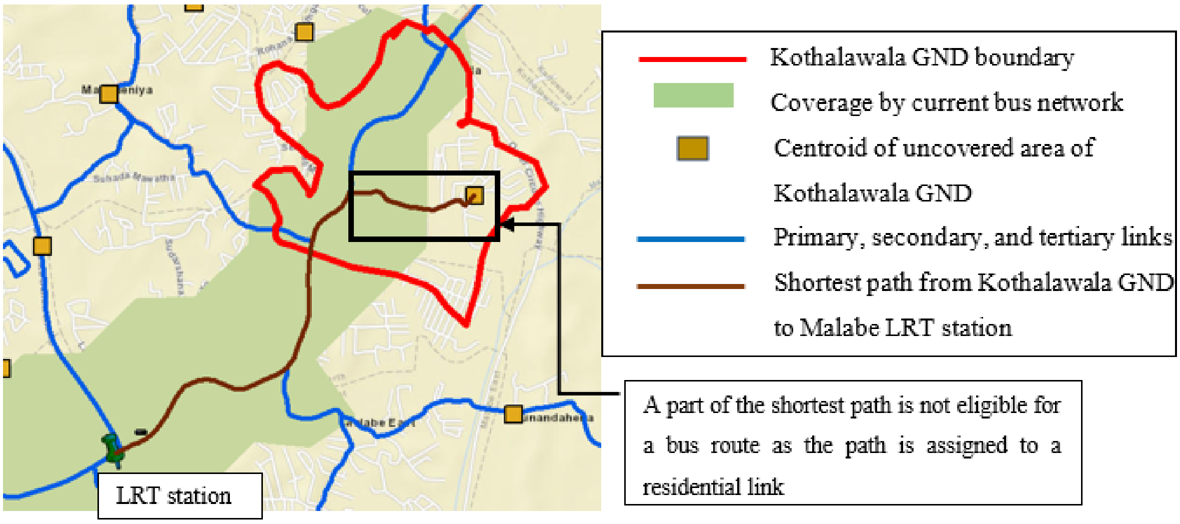


Figure 31: Residential Links Being Part of the Shortest Path

The cases where this issue arrise were identified and the centroids were adjusted to locate on the eligible links, while following the shortest path that was identified. For an example, for Kothalawala GND, the centroid was adjusted as in Figure 32.

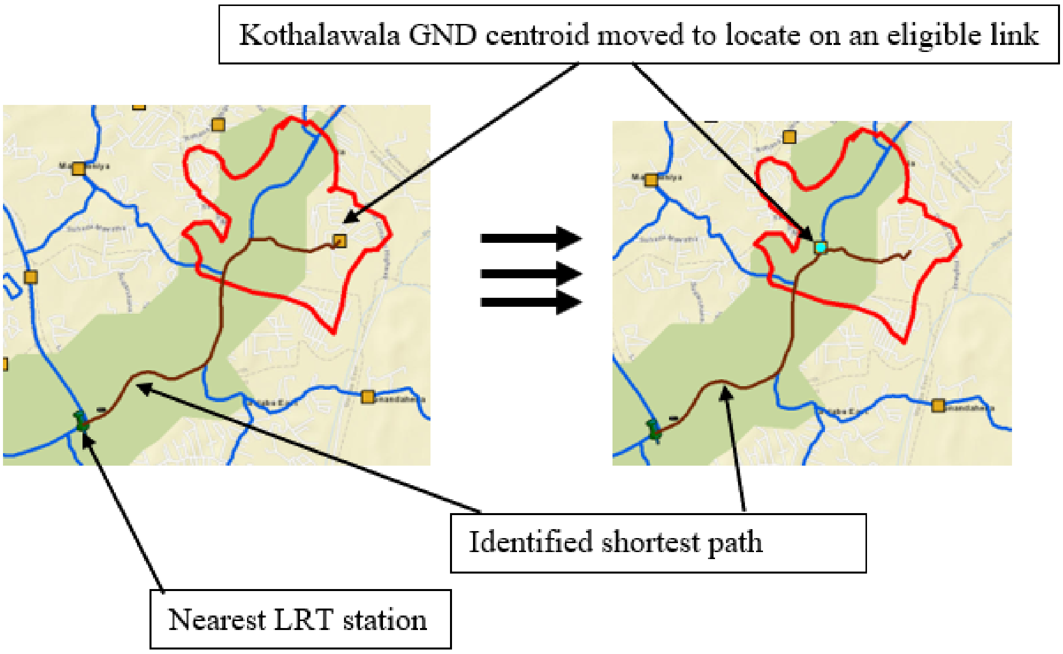


Figure 32: Relocation of GND

After the adjustments, again the shortest path network was generated and thereby, for each induvidual path, a separate bus route was introduced.

4.6.2 Design Method 2 - Designing a New Feeder Bus Network for Feeder Demand

The second design method to be followed is to design a new feeder bus network to cater to the demand or feeders completely where the existing network will not take part in supplying for the demand for feeders. In this method, only a dedicated feeder mode buses will operate in the catchment area. All connections between origins and the LRT stations are enabled directly by the feeder buses. The other OD pairs, such as two GNDs in the catchment are connected by either direct feeder buses, transfers of feeder buses or by transfers through the LRT. The objective in the method is to supply all GNDs inside the identified geographical area of 74.99km^2 with a bus feeder connection to the LRT rather than enabling connections between the GND zones directly with regular bus routes.

Therefore, it will encourage to travel by LRT. There will be no competitive bus routes that will be traveling parallel to the LRT, therefore, eliminating the congestion in the road segments parallel to the LRT.

In providing coverage to those areas by implementing feeder bus routes, the constraint implemented was bus routes being implemented in the shortest possible path, in links that were identified to have suitable road class. Several steps were identified to be followed.

1. Identifying the GNDs inside the geographical catchment area for bus mode
2. Identifying the centroids of GNDs considering the shape area
3. Identifying the shortest path links connecting the GNDs to the nearest LRT station
4. Implementing an individual bus route in each identified link above

4.6.2.1 Identifying the GNDs Inside the Geographical Catchment Area for Bus Mode

The GNDs inside the geographical catchment of bus mode, were identified to be 128, as in Figure 33. The GNDs and the area that was inlcuded inside the boundary of the catchment were considered.

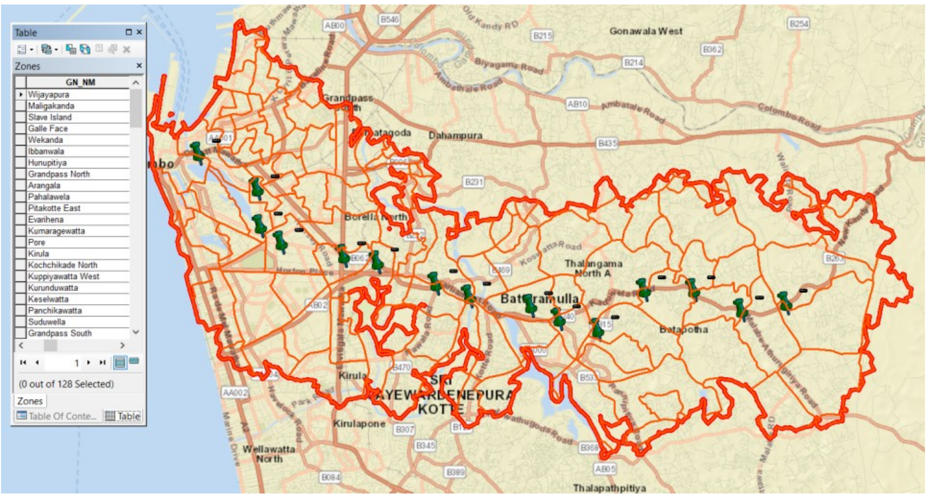


Figure 33: GNDs Inside the Geographical Catchment Area

4.6.2.2 Identifying the Centroids of GNDs Considering the Shape Area

The centroid of each GND was identified using Arc GIS as in Figure 34. For the centroids, the whole area of the GND was considered. These centroids, are considered to present the whole shape area of the GND.

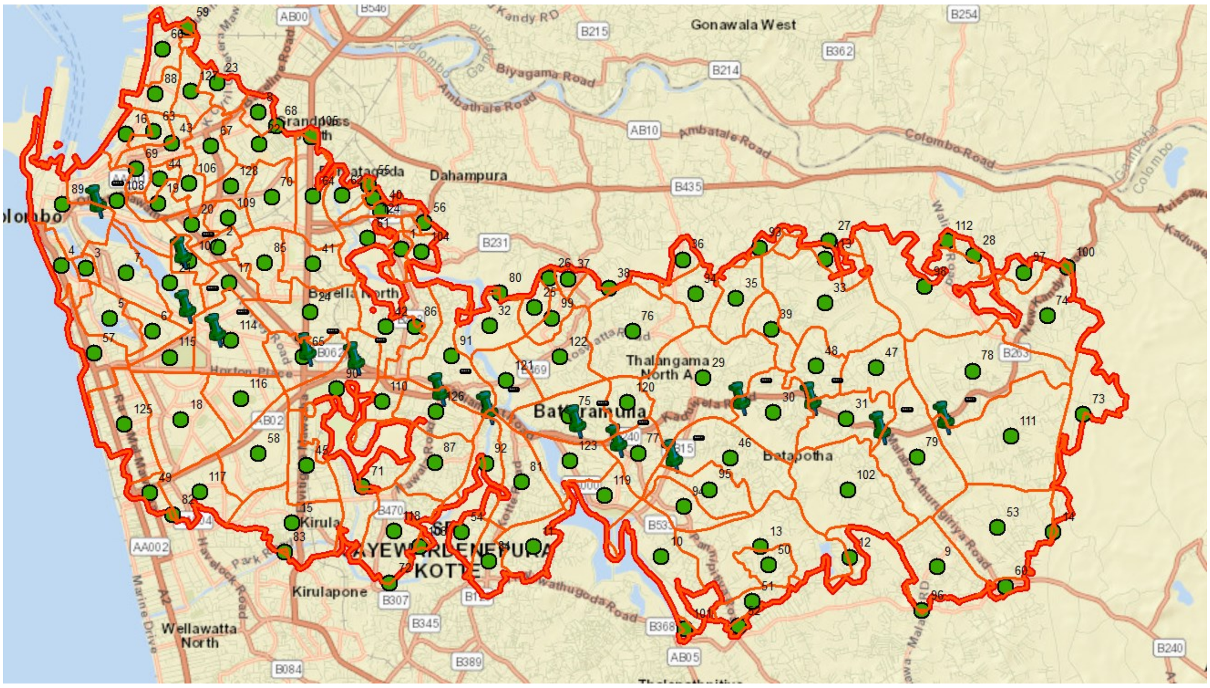


Figure 34: Centroids of GNDs

4.6.2.3 Identifying the Shortest Path Links Connecting the GNDs to the Nearest LRT Station

The shortest paths that were identified using the closest facility analysis is as in Figure 35. In this analysis as well, it was assumed that the passengers are willing to take the shortest route to reach the LRT station. As in network modification process before, in new network design process too uses the hierarchy of links to assign the paths. Hierarchy of links were as Primary, secondary, tertiary and residential. Therefore, the shortest paths were aligned in the upper hierarchy links first and lower hierarchy links such as residential links were only used to maintain the connection with the centroid, as the some of the centroids were only accessible by residential links.

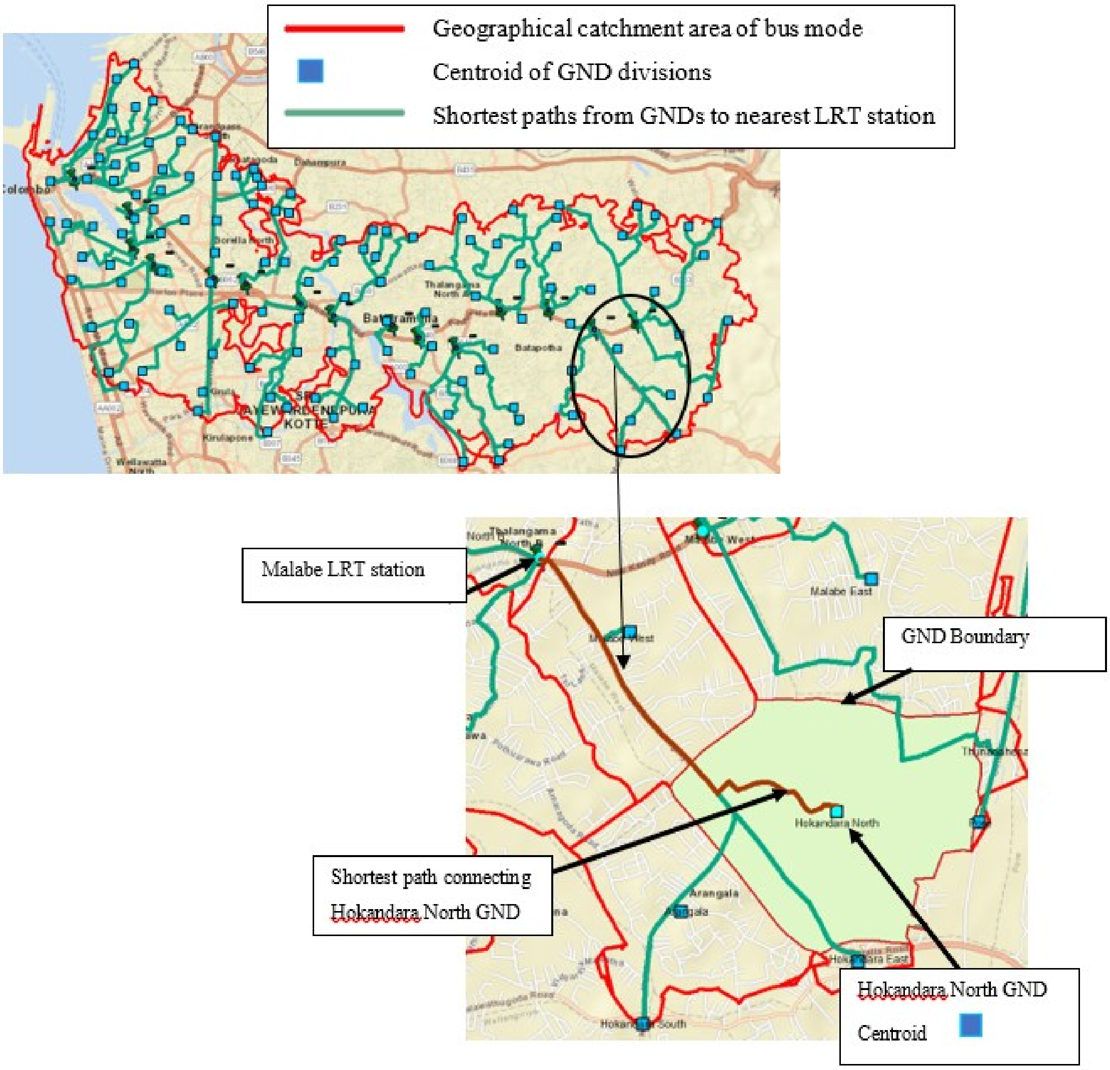


Figure 35: Shortest Paths Connecting GNDs to the Nearest LRT Station

4.6.2.4 Implementing an Individual Bus Route in Each Identified Link

An individual bus route was assigned to each of the shortest paths identified in the previous step, to analyze the coverage offered by these routes. In assigning a bus route, the factor of shortest path being aligned via a link that cannot accommodate a bus route was identified as a constraint.

Therefore, the shortest path route may align via several types of links such as primary, secondary, tertiary and residential. However, for the bus network, only primary, secondary and tertiary links (A, B, C and D classes) were considered. The identified links were shown previously in Figure 30. Therefore, the shortest paths where an ineligible link was assigned, were realigned so that they are aligned only in eligible links for a bus route. After adjustments, again the shortest paths were generated by Arc GIS and each of the shortest paths were assigned with a feeder bus route individually.

4.7 Evaluation of Accessibility by Different Strategies

After the two design methods were proceeded, namely, modifying the existing bus feeder network and then developing a bus feeder disregarding the existing network. After the design process, to measure the geographical coverage by the two methods, an area calculation was carried. By Arc GIS, the coverages by the current bus network and by the bus networks designed by two methods were visualized and evaluated.

4.7.1 Design Method 1 (Existing Bus Network Modification) Analysis

As the first method, the regular bus network was modified to include new feeder bus routes to connect the areas previously uncovered by the existing bus network. 115 GND were identified to have non or partial coverage by the existing bus feeder network out of the 128 GNDs in the full catchment area. Out of the 115 GNDs 114 GNDs were found with shortest paths to the nearest LRT station. Those paths were assigned bus routes, where each GND will be connected by an individual bus route. However, it can be seen that most of the bus routes that are introduced newly are partially overlapping with each other and the existing bus routes as well.

By Conveyal analysis, for each LRT station, the area that is accessible by bus mode was identified. Transit was enabled by the existing bus network, added bus routes and the LRT. Here as the time constraint, a time limitation of 20 minutes for bus mode travelling and 6 minutes for walking was allocated. It was assumed that the passengers will reach the bus stops by walking for the maximum duration 6 minutes and then board a bus to reach the LRT. The walking duration restriction was calculated based on the assumption of having 4km/h walking speed and maximum walking distance preference of 400m. Thereby, using Conveyal, the area that is supplied by the modified bus feeder was taken and visualized in Arc GIS as in Figure 36. Also, the visual comparison between the existing network coverage, modified network coverage and the catchment area is shown in Figure 37.

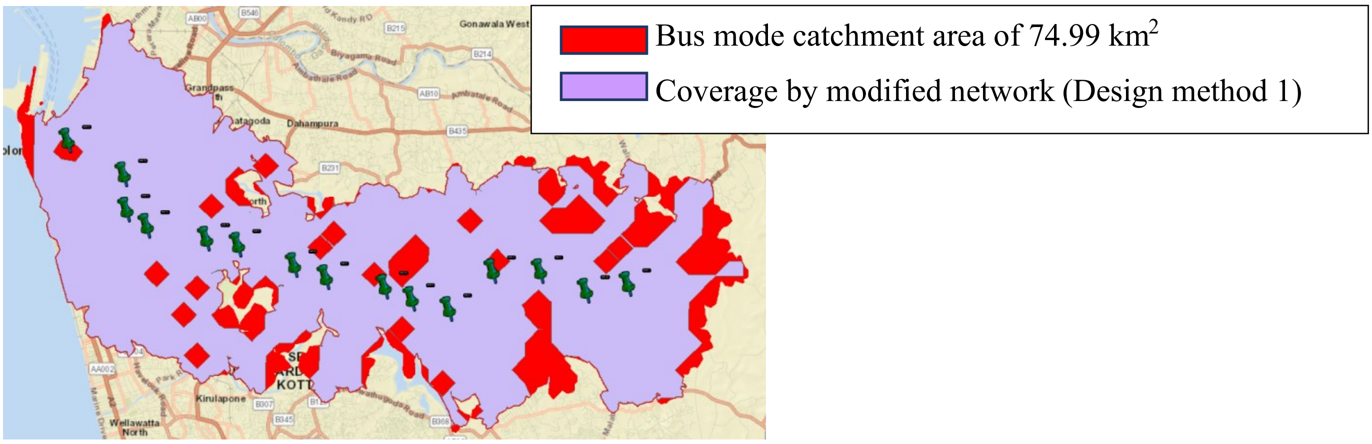


Figure 36: Comparison of Design Method 1 coverage with the Cathment Area

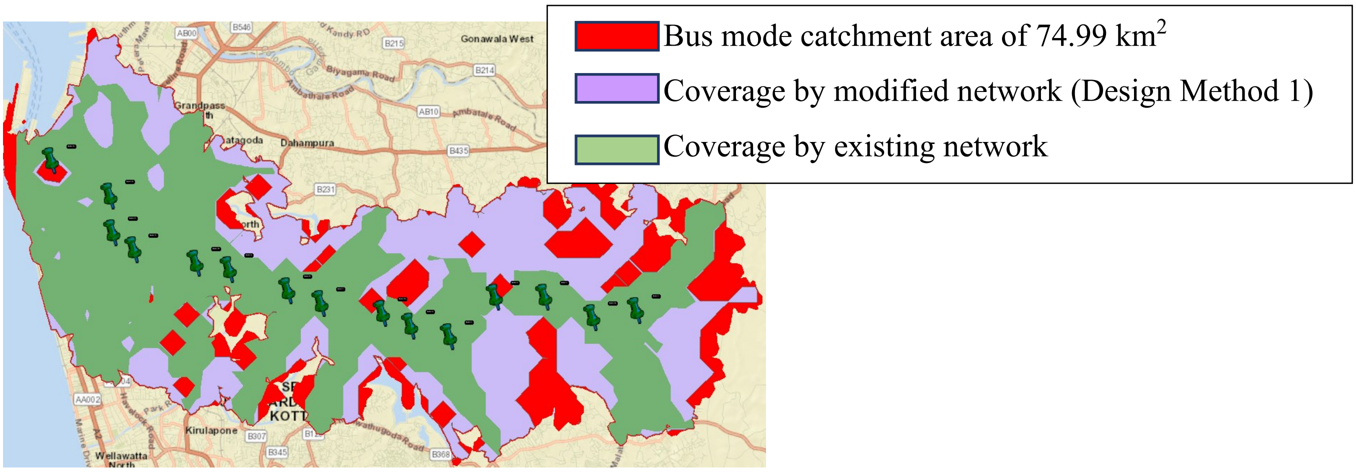


Figure 37: Comparison of Catchment with Coverages of design Method 1

From the visualizations, the coverage was quantified. The area covered of each GND was measured and it can be seen that 52 GNDs are having their area completely covered by the supply from modified network. Previously, in the current bus feeder, the number of GNDs that was covered fully was only 13.

And the overall coverage by the total modified network was taken as $62.15km^2$. In the current bus network, coverage was only $40.22km^2$. Therefore, the increment in coverage is significant. As a percentage it is a 55% increase. And by the modified network, 83.8% of the catchment is supplied.

4.7.2 Design Method 2 (New Feeder Bus Network Design) Analysis

The second method that was followed was to develop a Bus network which is a dedicated feeder network to access the LRT, disregarding the existing network. 128 GNDs were identified to be within the full catchment area. Out of the 128 GNDs 127 GNDs were found with shortest paths to the nearest LRT station. Those paths were assigned feeder bus routes, where each GND will be connected by an individual bus route. However, it can be seen that the bus routes feeding a specific LRT station are partially overlapping with each other.

By Conveyal analysis, for each LRT station, the area that is accessible by bus mode was identified. Transit was enabled by the newly assigned feeder bus routes and the LRT. Here as the time constraint, again a time limitation of 20 minutes for bus mode travelling and 6 minutes for walking was allocated as in the previous method analysis by assuming that the passengers will reach the bus stops by walking for the maximum duration 6 minutes and then board a bus to reach the LRT.

Thereby, using Conveyal, the area that is supplied by the newly developed bus feeder was taken and visualized in Arc GIS as in Figure 36. Also, the visual comparison between the existing network coverage, modified network coverage and the catchment area is shown in Figure 38.

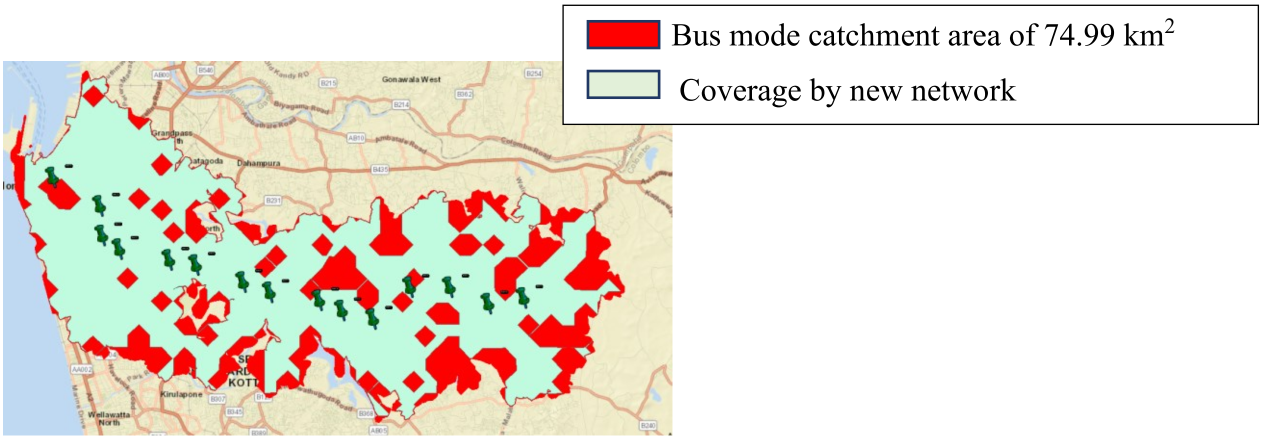


Figure 38: Comparison of Design Method 2 coverage with the Cathment Area

Figure 39 illustrates the coverage by the new network, compared to the coverage by the existing network.

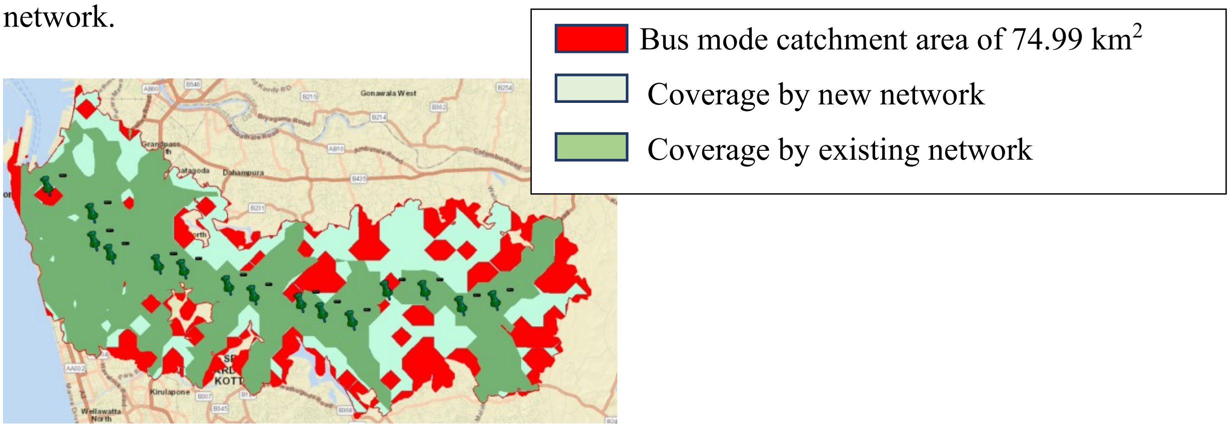


Figure 39: Comparison of Catchment Coverages of Design Method 2

The coverage by the newly developed network was quantified. The area covered of each GND was measured and it can be seen that 27 GNDs are having their area completely covered by the supply from newly developed network where in the current bus feeder only 13 GND's areas were covered completely.

And the overall coverage by the total modified network was taken as 54.25km^2. Therefore, the increment of 14.22km^2 can be seen compared to the current network. As a percentage it is a 35% increase. And by the modified network, 73.1% of the catchment is supplied where the present bus feeder coverage was only 45.8% of the total catchment area.

4.8 Selecting the Suitable Design Method Strategy

To identify the effectiveness of the design by two methods with respect to the current bus network, the area coverages at each instance were calculated and compared with the coverage by current network.

For each GND in the catchment area,

- Area coverage by existing bus network,
- Area coverage by modified existing bus network (Existing regular routes + new feeder routes)
- Area coverage by new developed bus network (Only feeder buses)

For each GND, above values were quantified. Examples area shown in Table 23.

Table 23: Comparison of Coverages by Existing Bus Network, Design Methods 1 and 2

			Existing bus network				Design Method 1 (regular + feeders)				Design Method 2 (feeders only)			
Zone_Code	Zone_Name	Shape Area of Zone inside the bus catchment	Covered Area	Percentage of Covered Area	Uncovered area	Percentage Uncovered	Covered Area	Percentage of Covered Area	Uncovered area	Percentage Uncovered	Covered Area	Percentage of Covered Area	Uncovered area	Percentage Uncovered
1103030	Aluthmawatha	31,913	0	0	31,913	100	28,848	90	3,065	10	28,785	90	3,128	10
1103035	Lunupokuna	402,429	17,035	4	385,394	96	361,106	90	41,322	10	220,415	55	182,014	45
1103040	Bloemendhal	348,795	0	0	348,795	100	347,963	100	832	0	293,499	84	55,296	16
1103045	Kotahena East	373,788	170,962	46	202,826	54	373,788	100	0	0	354,729	95	19,059	5
1103050	Kotahena West	334,877	191,958	57	142,918	43	334,877	100	0	0	325,115	97	9,762	3
1103055	Kochchikade North	270,780	132,623	49	138,157	51	265,592	98	5,189	2	265,589	98	5,191	2
1103060	Jinthupitiya	201,679	78,106	39	123,573	61	201,679	100	0	0	201,679	100	0	0
1103065	Massangasweediya	260,744	45,829	18	214,915	82	260,744	100	0	0	260,744	100	0	0
1103070	New Bazaar	507,682	456,190	90	51,492	10	507,682	100	0	0	507,682	100	0	0
1103075	Grandpass South	589,007	230,668	39	358,339	61	589,007	100	0	0	550,026	93	38,981	7
1103080	Grandpass North	232,235	18,532	8	213,702	92	232,235	100	0	0	153,755	66	78,479	34

Covergaes by the two design methods for all the zones are attached as Appendix B

However, when comparing the coverage by two methods themselves, it can be seen that modifying the existing network is more effective than implementing a new feeder network.

Yielded values are as in Table 24.

Table 24: Comparison of Coverages by Existing Bus Network, Design Methods 1 and 2

	Existing Bus Network	Design Method 1 (Modified Existing Network)	Design Method 2 (Newly Developed feeder bus network)
Bus Catchment Area (km^2)	74.15	74.15	74.15
Accessible area by bus feeder (km^2)	40.22	62.15	54.25
Inaccessible area by bus feeder (km^2)	33.92	11.99	19.9
Percentage of coverage (Coverage by feeder/catchment area*100) %	54.20%	83.80%	73.20%
Percentage of under coverage (Inaccessible area by feeder/catchment area*100) %	45.80%	16.20%	26.80%
Percentage increase of coverage compared to existing feeder network [(Accessible area by feeder design - Accessible area by existing network)/ Accessible area by existing network] * 100 %	0	55.50%	34.90%

The difference of coverage area by two methods was 7.9km^2 and as a percentage the difference of coverage was 10.6% of the bus catchment.

The reason for the better coverage is the larger number of bus routes. In the Existing Network Modification design method, existing bus network contains 102 bus routes operating in the catchment area considered and further 114 new bus routes as modifications. Some of the existing bus routes are parallel to the LRT hence competitive with the LRT. Also, when GND zones are considered, in design method 1, there are instances where two bus routes covering a single GND zone. In design method 2 however, for each GND, only one route is assigned and the whole network consists of only 127 bus routes. Therefore, it can be noticed that, implementing the design 1 can be constrained due to the limited resources.

In design method 2, the objective was to connect each GND in the catchment with the nearest LRT and the connection between the GNDs themselves were not focused upon. The GND OD pairs were to be connected through the LRT. No direct connections were pursued. Therefore, in the practical implementation, even though it is an ideal feeder system for the LRT, passengers may face certain difficulties. Also, the social issue of the change in the familiar bus network may also factor in. the present bus routes are established and the awareness of them is high. But in introducing a new bus network, different from the network that passengers are familiar with, passengers can take a certain time to adapt.

Therefore, below criteria were focused upon in order to select the best design method.

- Effective coverage of the catchment area
- Availability of resources to implement the bus network
- Social impact by the implementation of the bus network

Considering the effective coverage, it was identified that the design method 1 (modifying existing bus network) was more effective.

As per the resources, even though the resource requirement of the design method 1 was higher than in design method 2, the newly implementing bus routes can be operated using mini buses. This will be viable as the demand is already partially supplied by the existing network. Therefore, the excess demand may be handled adequately by using mini buses. However, this research does not further analyze the issue of resource limitation.

In the aspect of social impact as well, we may assume that the design method 1, modifying the existing bus network is less disruptive than the design method 2, Introducing a new feeder network, completely disregarding the existing bus network. However, the social impact is also not further analyzed in this research.

4.9 Bus Feeder Design Optimization

In designing the feeder method, in both the scenarios, modifying the existing bus network and developing a new bus network, all identified shortest paths connecting each GND with the nearest LRT was assigned a separate bus route. However, in practical scenario, assigning a bus route for each path will not be the optimum solution or practical solution due to the limitation of resources.

In the previous step the effectiveness of the two design methods were analyzed by their area coverage and the higher impact method was identified. By the analysis it was seen that modifying the existing network is far more suitable. This selected feeder network needs to be optimized to yield the highest coverage of catchment area while being cost effective with the minimum impedance. This may be carried out by methods such as route merging, route breaking etc. However, in order to identify which routes can be merged and braked, following steps were followed.

1. Developing the bus route grid
2. Calculating Demand by each GND
3. Ranking of demand
4. Assigning demands to the developed grid
5. Optimizing the route network

4.9.1 Route Grid Development

From the bus network design, it can be observed that multiple feeder routes are connecting to a single LRT station. An example is shown in Figure 40.

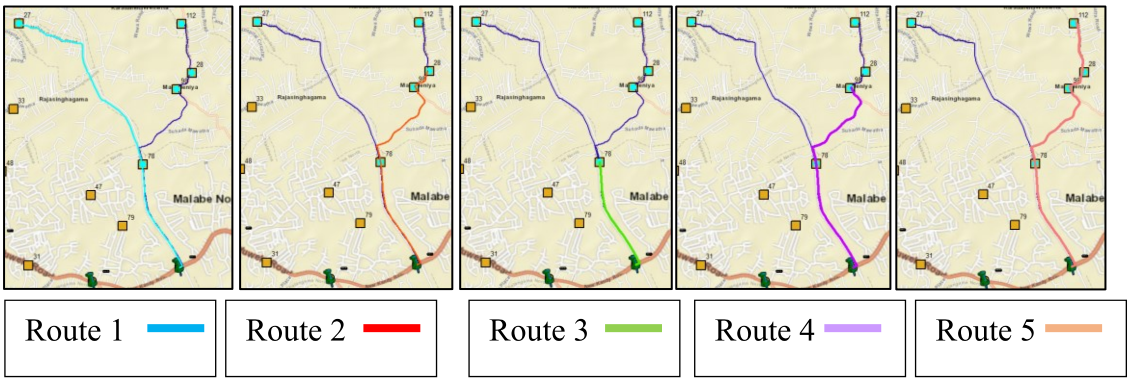


Figure 40: Different Bus Routes connecting to the Same LRT station

The connections of each LRT station are as in Table 25.

Table 25: The Connections of Each LRT Station

LRT Station	Number of feeder buses connecting Design Method 1 (Modifying existing bus network)	Number of feeder buses connecting Design Method 2 (Designing new feeder network)
Malabe IT park	11	11
Malabe	6	8
Thalahena	6	5
Lumini Temple	7	8
Robert Gunawardhana Mawatha	9	9
Battaramulla	2	3
Sethsiripaya	2	2
Rajagiriya	11	11
Welikada	11	10
Cotta road	7	5
Borella	13	17
Townhall	5	6
Ibbbanwala	5	10
Maradana	4	4
Pettah	16	18
Total	115	127

Therefore, considering each LRT station, and the feeders that connect to them, a grid was developed which had following features.

- Links based on road network
- Nodes based on GNDs and LRT stations
- The lengths of the links are in scale to the actual lengths of the road network link.

A sample of the grid is shown in Figure 41.

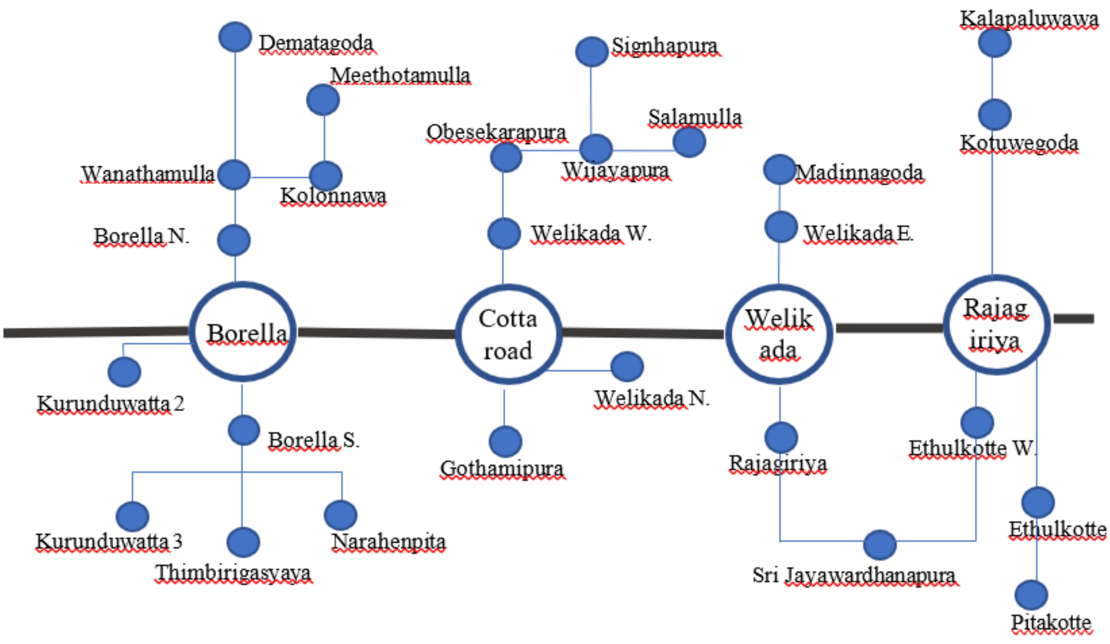


Figure 41: Sample of the Bus Routes Grid

4.9.2 GND Demand Calculation

For each GND, the demand towards the feeder buses was calculated. To calculate the demand, the following factors were taken in to account.

- Area of expected coverage of GNDs by bus network
  The area coverage by the designed bus network of each GND was taken for the demand calculation of each GND.
- Area of coverage by regular bus routes
  When the number of regular bus routes connecting the GND and the LRT operating is

higher, the demand for the feeder will reduce. Therefore, the existence of regular routes was also taken in to consideration.

- HH density of GNDs
  For each GND, the density of HHs throughout the GND was taken
- Passenger rate per HH for Fort – Malabe corridor
  From the stated preference survey data, the number of respondents and the number of HHs that they belonged to were identified and hence the generation rate of passengers using the LRT per HH was calculated for the corridor.
- The percentage of preference for bus feeder in Fort – Malabe corridor
  From the stated preference survey, the percentage of passengers preferring bus feeder from the total passengers using a feeder was taken for the Fort – Malabe corridor

Therefore, taking all above factors in to account, equations to derive the demand from each GND and a then a ranking factor for each GND for the bus feeder network was developed as follow.

Equation 3

$$Di = [Area\ Bus\ Network\ (i) - Area\ Regular\ (i)] * HHD(i) * PGR * Pb$$

Di – Demand of the GND i

Area Bus network (i) –Area of coverage by the bus network in GND i. The bus network considered is the design network that was selected in bus network design analysis.

Area Regular (i) –Area coverage by regular bus routes only in GND i

HHD(i) – House Hold density of GND i

PGR – Passenger generation rate per HH for Fort – Malabe corridor

Pb – Percentage of passengers selecting bus feeder for Fort – Malabe corridor

By the stated preference survey data, it was calculated, for Fort – Malabe corridor,

PGR = 1.19 per HH

Pb = 22.5%

HHD (i) =Number of HH in GND i / Shape area of the GND i inside the catchment area

Equation 4

$$Area\ Feeder\ (i) = Area\ Bus\ Network\ (i) - Area\ Regular\ (i)$$
$$= (\text{Area of coverage by the bus network (feeder + regular) in GND i}$$
$$- \text{Area coverage by regular bus routes in GND i})$$

For each of the design methods, equation 3 can be applied as follows

For design method 1,

Both regular bus routes and feeder routes are operating in the bus network design. Regular bus routes are similar to the bus routes in the existing bus network. Therefore,

Area Bus Network = The area that was identified to be covered in GND i by the bus network design 1, which consists of the existing regular routes and added feeder routes.

Area Regular = Area covered in GND *i* by the existing bus network.

As shown in Table 23, for each GND inside the bus feeder mode catchment area, those above values were identified previously. Therefore, can be substituted.

Example: Arangala GND

Area coverage by Bus Network Design 1 (Arangale) = 1,001,945 m^2

Area coverage by Regular (existing) bus network (Arangala) = 876,535 m^2

For design method 2,

Only feeder routes are operating in the bus network design. No regular bus routes. Therefore,

Area Bus Network = The area that was identified to be covered in GND i by the bus network design 2, which consists of feeder routes.

Area Regular = 0

As shown in Table 23, for each GND inside the bus feeder mode catchment area, those above values were identified previously. Therefore, can be substituted.

Example: Arangala GND

Area coverage by Bus Network Design 2 (Arangale) = 747,447 m^2

Area coverage by Regular bus network (Arangala) = 0

Thereby, the demand occurring at each GND can be calculated.

4.9.3 Hierarchy of Demand

A hierarchy of demands was generated taking the demand and the distance between the GND and the connecting LRT station as the weighting factors.

The distance from the GND centroid to the nearest GND was taken to be influencing the number of people that will select bus mode as their feeder rather than other feeders. The percentage of passengers selecting the bus feeder from the total number of passengers using feeders, was taken considering the Fort - Malabe corridor. This percentage was not calculated for each GND due to the limitations in data. However, when the distance to travel by the feeder mode is increasing, there is a higher chance of a passenger selecting bus feeder as their feeder mode rather than another feeder mode. Therefore, the route distance was used as a weighting factor for the ranking.

Hence the following equation was derived to calculate the weighted demand.

$$WD(i) = Di * L(i)$$

WD (i) = Weighted Demand of GND i

Di = Demand of GND i

L(i) = Length of bus route connecting GND i with the nearest LRT station

For design method 1, demands of GNDs and rankings of feeder bus routes can be derived as in Table 26.

Table 26: Demands of GNDs and Rankings of Feeder Bus Routes in Design Method 1

GND name	Zone ID	LRT station connected to	Area coverage by bus network	Area coverage by regular bus routes	Area coverage only by feeder bus routes	HHD (i)	PGR	Pb	Demand (i)	L(i)	Weighted Demand	Rank
			Area Bus Network (i)	Area Regular (i)	Area Feeder (i)	(Number of Hhof GND i)/ (Shape area of GND i)	Number of passengers/ Number of HH	Number of passengers usig bus mode/ Number of passengers using a feeder mode	[Area Feeder (i) *HHD(i)*PGR*Pb]		D(i) * L(i)/1000	
			m2		m2	HH/km2	Passengers/HH		Passengers	m	Passengers *km	
Grandpass South	1103075	Maradana	589,007	230,668	358,339	6249	1.19	0.225	600	3271	1961	1
Kirula	1127075	Borella	979,715	356,448	623,267	2773	1.19	0.225	463	3038	1406	2
Walpola	1109155	Lumbini	1,275,893	85,997	1,189,895	1442	1.19	0.225	459	2321	1066	3
Bloemendhal	1103040	Petta	347,963	0	347,963	3244	1.19	0.225	302	3377	1021	4
Grandpass North	1103080	Petta	232,235	18,532	213,702	4850	1.19	0.225	278	3307	918	5
Lunupokuna	1103035	Petta	361,106	17,035	344,072	2652	1.19	0.225	244	3318	811	6
Kotahena East	1103045	Petta	373,788	170,962	202,826	4192	1.19	0.225	228	3257	742	7
Himbutana East	1106175	Lumbini	578,813	0	578,813	1507	1.19	0.225	234	3003	701	8

For design method 2, demands of GNDs and rankings of feeder buses can be derived as in Table 27.

Table 27: Demands of GNDs and Rankings of Feeder Bus Routes in Design Method 2

GND name	Zone ID	LRT station connected to	Area coverage by bus network	Area coverage by regular bus routes	Area coverage only by feeder bus routes	HHD (i)	PGR	Pb	Demand (i)	L(i)	Weighted Demand	Rank
			Area Bus Network (i)	Area Regular (i)	Area Feeder (i)	(Number of Hh of GND i)/ (Shape area of GND i)	Number of passengers/ Number of HH	Number of passengers usig bus mode/ Number of passengers using a feeder mode	[Area Feeder (i) *HHD(i)*PGR*Pb]		D(i) * L(i)/1000	
			m2		m2	HH/km2	Passengers/HH		Passengers	m	Passengers*km	
Kurunduwatta 4	1127019	Townhall	1,407,789	0	1,407,789	4,943	1.19	0.225	1863	3186.9459	5938	1
Grandpass South	1103075	Maradana	550,026	0	550,026	6,249	1.19	0.225	920	3242.7259	2984	2
Dematagoda	1127030	Borella	656,868	0	656,868	5,211	1.19	0.225	917	2307.644	2115	3
Kurunduwatta 3	1127018	Borella	575,377	0	575,377	4,943	1.19	0.225	762	2676.7112	2038	4
Narahenpita	1127055	Borella	524,164	0	524,164	4,038	1.19	0.225	567	3008.711	1705	5
New Bazaar	1103070	Petta	507,682	0	507,682	4,926	1.19	0.225	670	2437.8907	1633	6
Thimbirigasyaya 2	1127062	Borella	818,208	0	818,208	3,015	1.19	0.225	660	1999.2902	1320	7
Kotahena West	1103050	Petta	325,115	0	325,115	5,495	1.19	0.225	478	2645.7537	1266	8

4.9.4 Assigning Demands to the Developed Grid

The bus feeders that were previously identified were applied to the road network in the bus network design step. However, to optimize the bus routes by methods such as merging, breaking etc. first the demand generated by the bus routes at each link in the network requires to be identified.

Therefore, demands that are carried out by each bus route was assigned to the relevant links that are aligned in that feeder bus route path. The demand assignment was carried out by the rank, giving the priority to higher ranking ones. This can be done for either of the discussed design method. A sample assignment is shown in Table 28 and Figure 42.

Table 28: Sample Assignment of Demand and Rank

GND name	LRT station	Demand (i)	Rank
A	LRT 1	1000	1
B	LRT 1	800	2
C	LRT 1	500	3
D	LRT 1	200	4

Bus routes

A → LRT 1, Link 2 → Link 1

B → LRT 1, Link 4 → Link 3 → Link 1

C → LRT 1, Link 5 → Link 3 → Link 1

D → LRT 1, Link 6 → Link 5 → Link 3 → Link 1

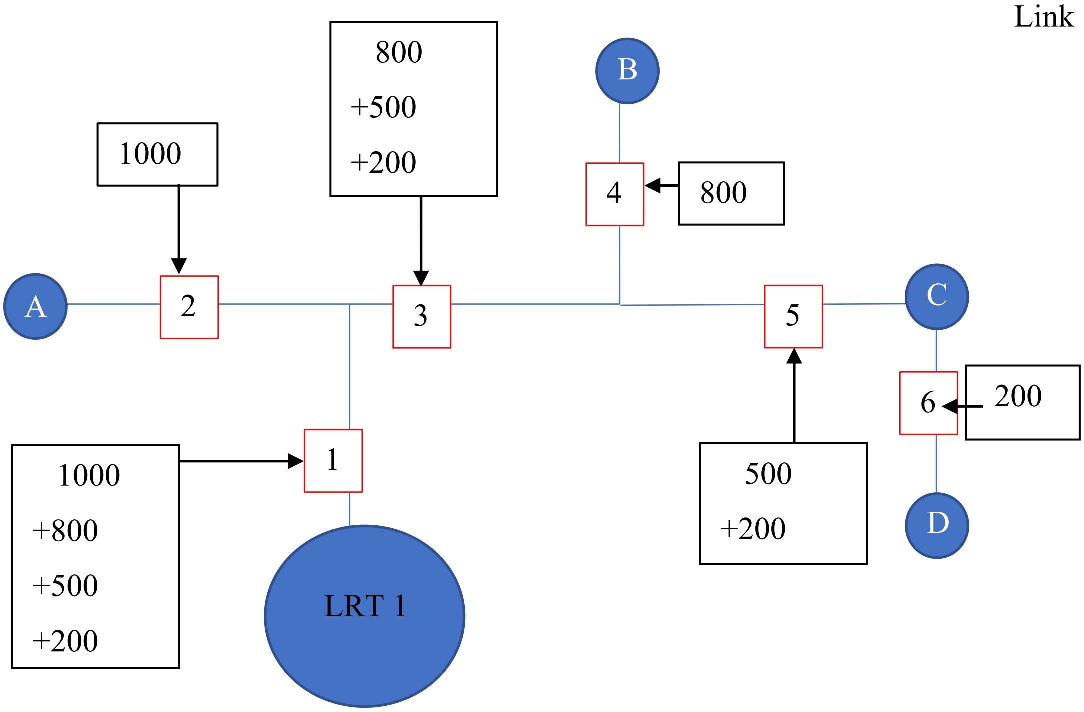


Figure 42: Sample ssignment of Demand

After assigning the demands, the demands in each link can be identified clearly.

4.9.5 Optimization of Feeder Network

As the next step, the bus routes that were assigned, were inspected again by the order of their rank to identify how the bus routes can be adjusted to reach an optimum network. In this case, only route merging was considered rather than the route breaking, since these routes were only of lengths 3.3 km or less.

For design method 1, feeder routes may merge with each other or merge with an existing regular bus route.

For design method 2, feeder routes may merge with each other.

For the above case sample, let's consider the design method 1, while assuming there is a regular bus route established passing through the links 5-3-1 as shown in Figure 43.

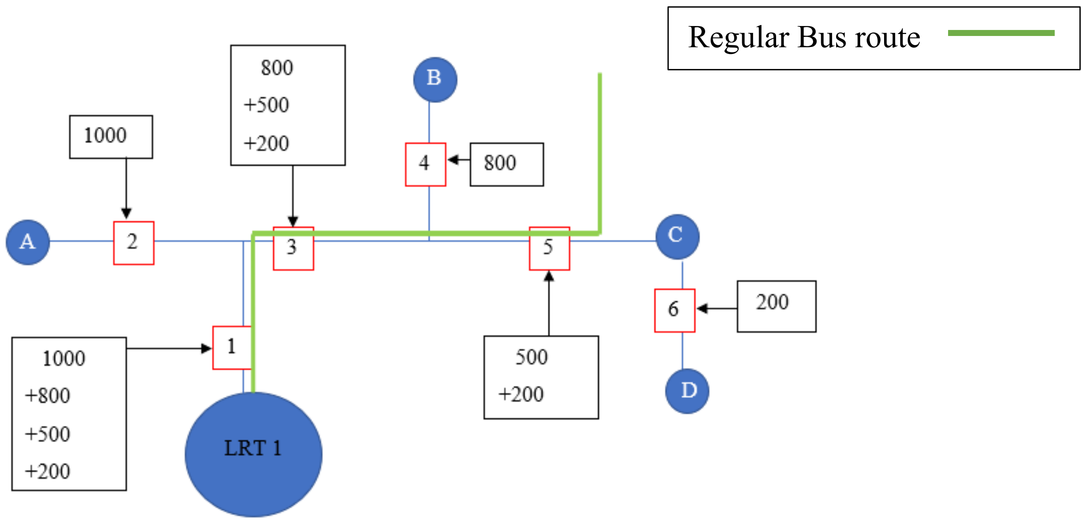


Figure 43: Sample Assignment

Each route is considered by rank and each feeder route is decided upon how to modify. This modification decisions are based on the analyzer, limitation of resources, existing bus route quality etc.

The highest ranked feeder route is A-LRT1. There are, no higher ranked feeder route to merge it with. Therefore, an individual feeder route is added to A-LRT1 path.

Second ranked route is B-LRT1 route. This route partially overlaps with a current route. Therefore, one option is to merge with the regular route. However, B-LRT1 route derives a high demand in Link 4 and if this route was merged with the regular route, the regular route might not possess the required capacity to handle that demand. Therefore, a second feeder route is added to B-LRT1 path.

The third ranked feeder route is C-LRT1 route. Again, it overlaps with the regular route. This route has a relatively lower demand. Therefore, the options merging with the regular route and having a separate feeder route both can be taken to be valid. The decision will depend on the availability of the resources. If a separate feeder is added, the feeder can be operated using mini buses instead of the higher capacity buses. As mentioned before, the decision depends on the analyzer and the availability of resources.

The last route is D-LRT1 route which has a low demand. However, it can be seen that the route overlaps with C-LRT1 route and the regular route as well. In that case, the options are merging it with either C-LRT1 route or merging it with the regular route. The best option in this case may be merging with the C-LRT1 route and implement the "D-C-LRT 1" route with the capacity of 700 (500+200) so that route can supply to both GND C and GND D.

Therefore, the final bus feeder network connecting to the LRT1 may look as follows with respective capacities as shown in Figure 44. Instead of the 4 feeders as in the initial design, now the network operates with 3 feeder bus routes and the regular bus routes. The demand that was assigned to the feeders was the demand that was not satisfied by the regular routes.

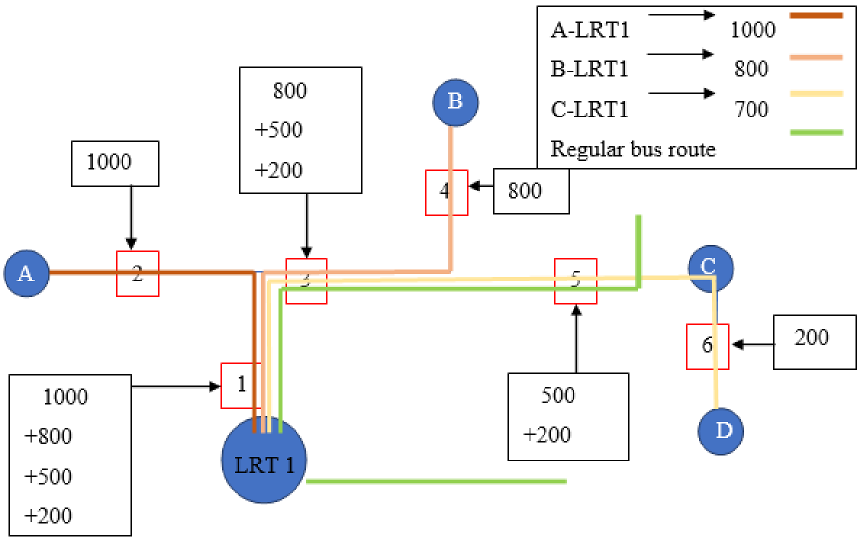


Figure 44: Sample Optimized Bus Feeder Network for LRT station 1 – Option 1

Another option can be breaking and reshaping the existing regular bus route. For an example, if the regular bus route, that is operating currently, supplies to a varying demand, such as low demand at the initial links and then a high demand at link 1,3 and 5, the regular route can be broken. In that case, instead of providing a separate feeder covering GND D and GND C as in previous optimization, the existing regular route may be broken in to two regular routes and they may take two different paths as shown in Figure 45 as R1 and R2. R1 will respond to the demand at the initial links in the regular route, that are not applicable for feeder connections. R2 will respond to the demand by GND D and GND C. The combined capacity of R1 and R2 will deliver to the demand in link 5 and combination of R1, R2 and B-LRT1 routes will deliver to the demand in link 5 and combination of R1, R2, B-LRT1 and A-LRT 1 will supply for the demand in link 1 shown in Figure 45.

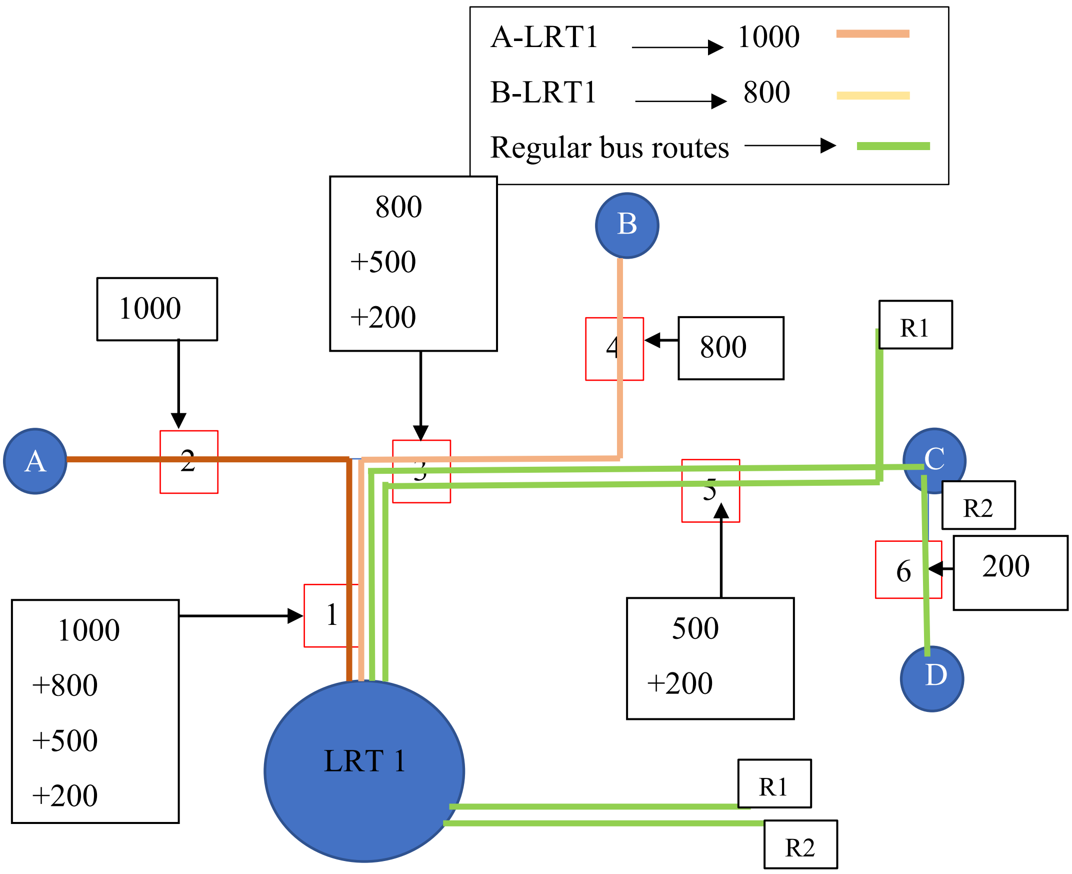


Figure 45: Sample Optimized Bus Feeder Network for LRT station 1 – Option 2

Therefore, the final design will be two regular routes and two feeders.

For design Method 2, the same procedure can be followed, except for following the option of merging with a regular route.

4.9.6 Application of Optimization

As for the Fort -Malabe corridor, the design method 1 was selected. Therefore, the optimization procedure can be applied to the identified bus network, which is the bus network derived by modifying the existing bus network.

For an example, for Lumbini LRT station, 5 feeder routes can be seen feeding with demands an in Table 29 and Figure 46.

Table 29: Demands and Ranks of Zones Connecting to Lumbini LRT station

GND Name	GND number	Zone number	LRT station	Demand (i)	Rank
Walpola	76	1109155	Lumbini	1066	3
Himbutana East	35	1106175	Lumbini	701	8
Himbutana West	34	1106180	Lumbini	562	13
Thalangama North A	29	1109150	Lumbini	274	30
Udumulla South	39	1106170	Lumbini	239	34
Mulleriyawa South	36	1106145	Lumbini	237	36
Malgama	93	1106150	Lumbini	115	55

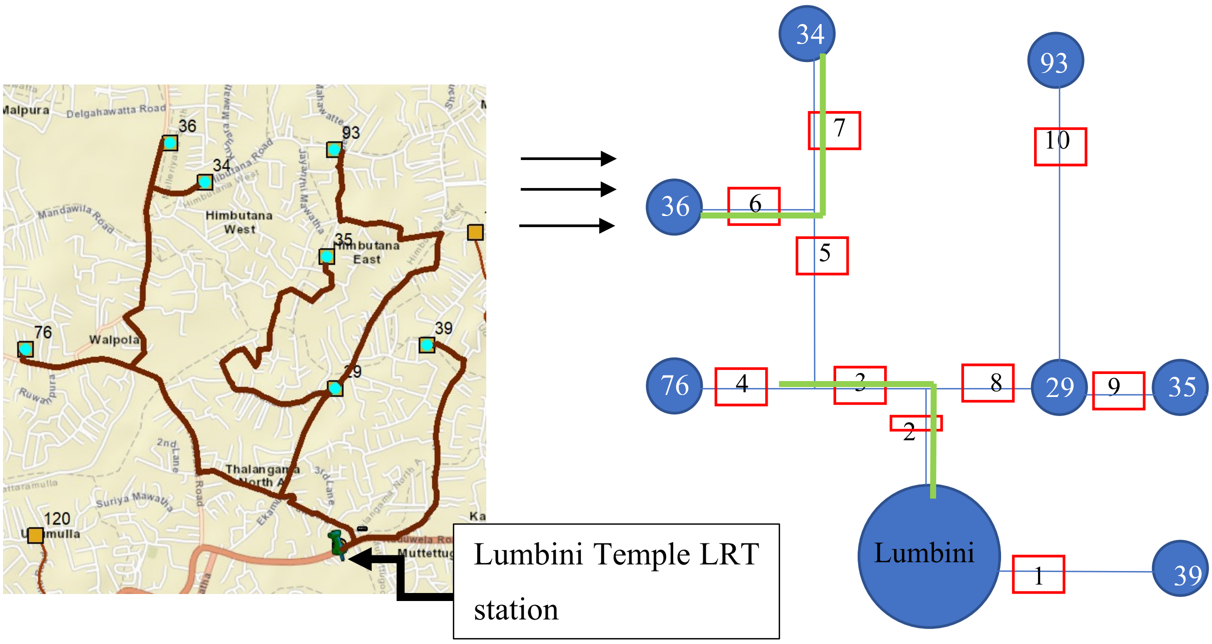
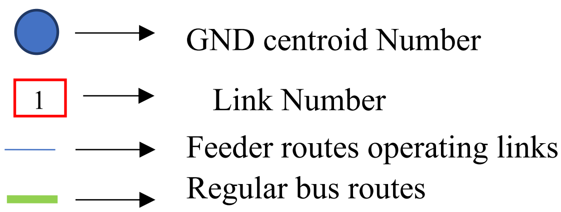


Figure 46: Feeder route grid for Lumbini Station



Initially from each GND centroid, a feeder route is operating, connecting with the Lumbini LRT station.

After identifying the grid connection, demand can be assigned to the network as in Figure 47.

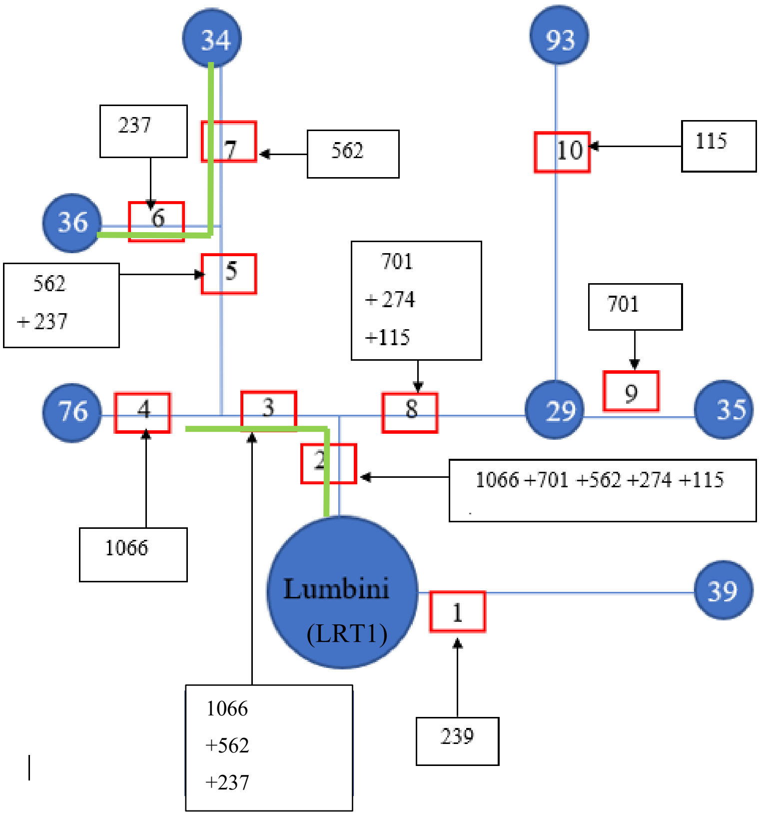


Figure 47: Demand Assignment for Lumbini LRT Station

hereby, each route is considered by the order rank.

The highest ranked feeder route is 76-LRT1. There are, no higher ranked feeder route to merge it with and it contains a high demand. Therefore, an individual feeder route is added to 76-LRT1 path. However, this feeder route partially overlaps with a regular route. Even though merging with the existing route is an option, due to the feeder alone having a high demand, best option will be to implement a separate feeder route.

Second highest rank is by the GND 35 and it is not overlapped, by other higher-ranking feeder or a regular bus route. Therefore, a separate feeder route is added as 35 – LRT1.

Third ranked route is 34-LRT1 route. This route partially overlaps with a regular route. Therefore, one option is to merge with the regular route. However, 34-LRT1 route derives a high demand and the route is only partially overlapped by the regular route and if this route was merged with the regular route, the regular route might not possess the required capacity to handle that demands. Therefore, a feeder route is added to 34-LRT1 path.

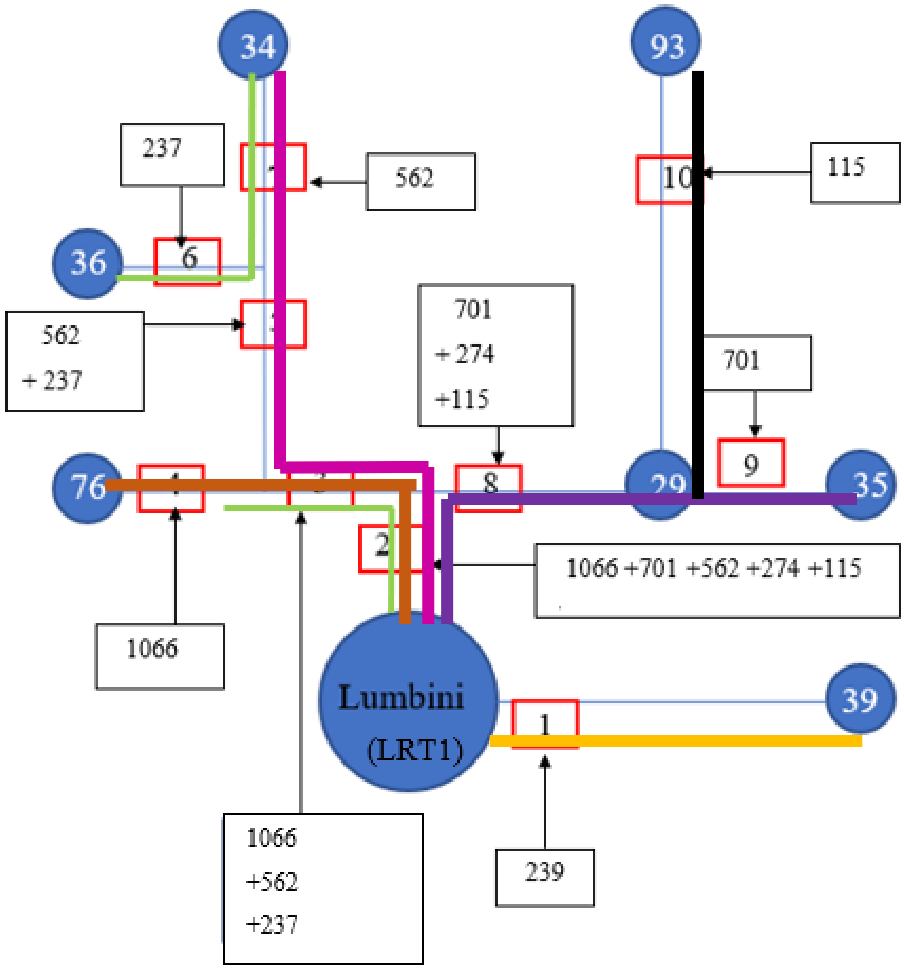
The fourth ranked feeder route is 29-LRT1 route. It completely overlaps with the route 35-LRT1. Therefore, the routes can be merged by altering the route 35-LRT1 to have the combined capacity of 35-LRT1 and 29-LRT1.

The next route is 39-LRT1 route which is not overlapped by other higher-ranking feeder or a regular bus route. Therefore, a separate feeder route is added as 39 – LRT1. As the demand is relatively less, mini buses or medium capacity buses can be used.

6th bus route is the 36-LRT1route, which has a relatively low demand and which also overlaps with a regular route and also a higher ranked feeder bus route. Therefore, 36-LRT1 route is merged with both the regular route and the 34-LRT1 route. The passengers can access the LRT station by transferring between the two routes.

Last route is 93-LRT1 route. This route has low demand and it partially overlaps with the 35-LRT1 route. Therefore, the 93-LRT1 route can be merged with 35-LRT1 route. However, as the length of link 10 is higher comparatively, a mini bus route, which will enable the transfers between centroids 93 and 29. Passengers from GND 93 may transfer from the mini bus route to the feeder route to reach the LRT.

Therefore, the final resulting bus network will be as follow shown in Figure 48.



Regular bus routes

76 – LRT 1 route (Capacity = 1066)

35 – LRT 1 route (Capacity = 1090)

34 – LRT 1 route (Capacity =799)

39 – LRT 1 route (Capacity = 239)

98 – LRT 1 route (Capacity = 115)

Figure 48: Optimized Bus Network for Lumbini LRT Station

However, it is important to note that the optimization process will heavily depend on the judgement of the designer. Especially merging with existing routes, breaking existing regular routes, reshaping the regular routes may be based on the demand fluctuations through the path that route takes as discussed in the general example.

Therefore, defining a define method for optimization is too complex and it is rested on the decision making of the designer. Only guidelines may be presented as below.

1. Route Merging

   Route merging can be carried out when several routes are terminating at the same node and when there are possible ways to join the routes. Also merging may carried out when a feeder route can be merged with a regular bus route, where regular bus routes are operating alongside the feeders.

   The decision of merging can be taken where partial or full overlap is visible between routes. In merging, firstly the highest ranked route is selected firstly, which is based on the demand, and the priority is given to the higher ranked route and an individual route is implemented at first for the higher ranked route and then lesser ranked other routes are investigated on how to merge with the higher ranked routes to avoid the highest number of transfers.

   The total distance, transfer savings, requirement of the number of buses may be the determining factors. Merging might not be cost effective for low passenger demands or in cases where a very high fleet size is required to accommodate the combined demands of several routes.

2. Route Breaking

   Route breaking decision may be taken in cases where a certain link holds a lower demand compared to the other links in the path of a certain route. In that case it would be economical to break the route and operate a separate lower fleet size route in the low demanded links. Demand variation justifying the route breaking is shown in Figure 49.

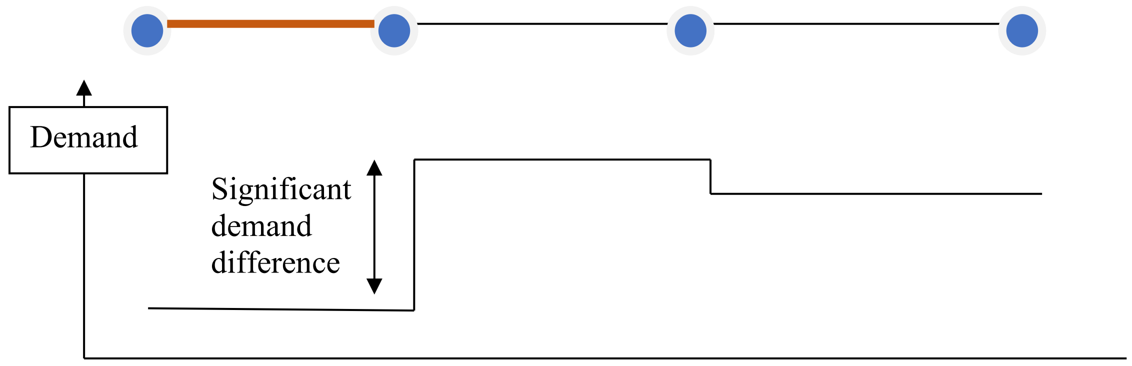


Figure 49: Demand Variation of a Route Justifying Route Breaking

In the case as above, where the first link is having a very low demand assigned to it, the first link may be broken off and operate as a separate route with less frequency.

3. Route Sprouting

   Route sprouting may be exercised where a certain link in the path of a route shows a very high demand relative to other links of that route. In those cases, new routes which will overlap the existing routes may be introduced to accommodate the relatively high demand on those links. The sprouted routes will only operate in the high demanded links. Demand variation justifying the route sprouting is shown in Figure 50.

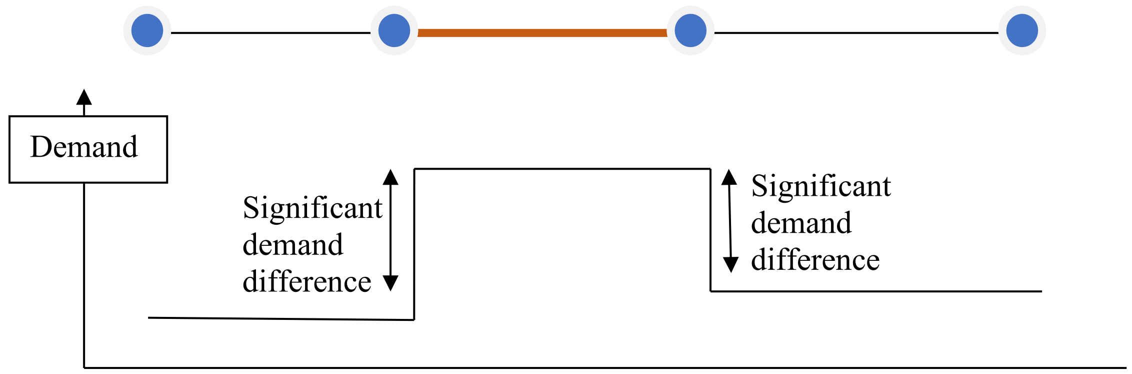


Figure 50: Demand Variation of a Route Justifying Route Sprouting

4. Route Reshaping

   Routes, especially the exiting regular routes may be reshaped, in order to accommodate a feeder route, which is partially overlapping with a regular route in a manner that will not disturb to the existing operating demand of that regular route. Demand variation justifying the route re-shaping is shown in Figure 51.

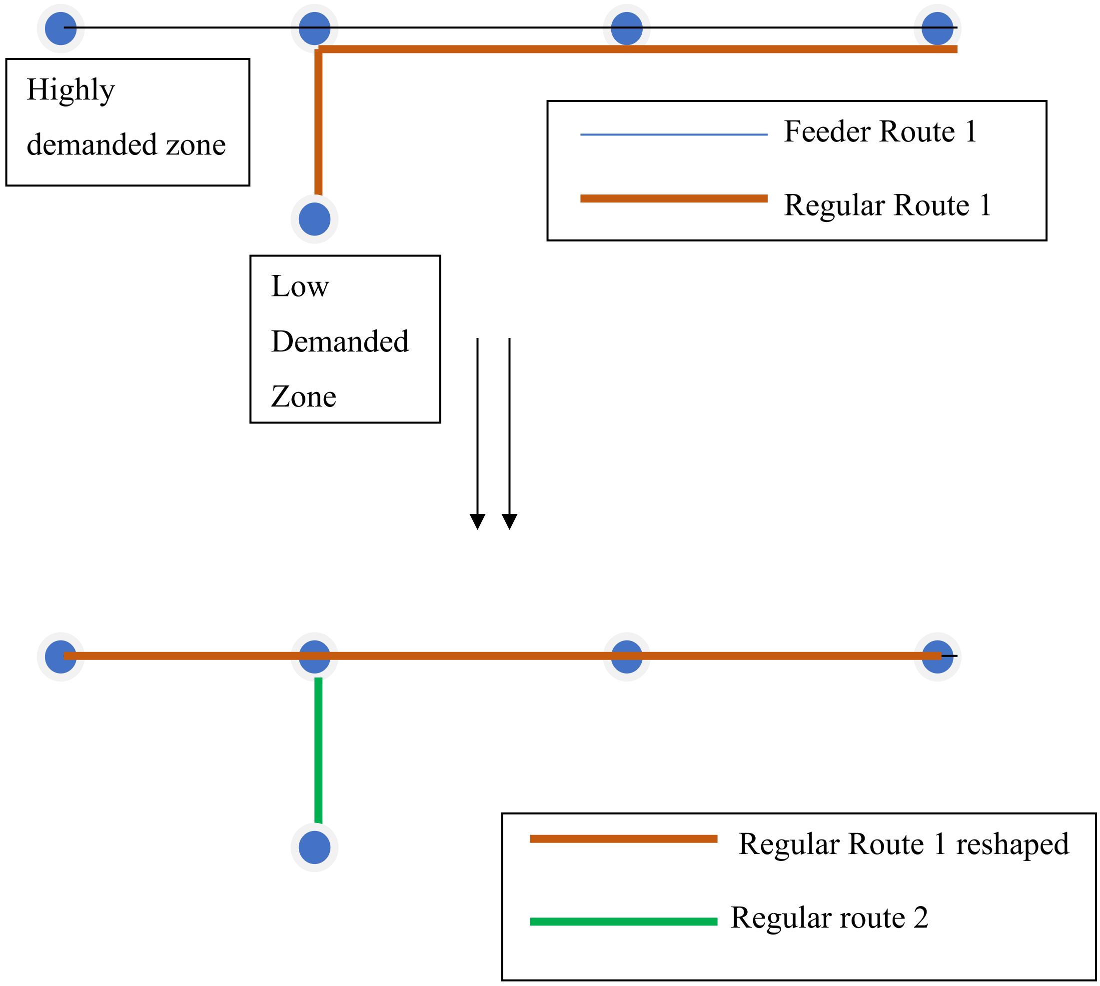


Figure 51: Regular Route Reshaped

Feeder route 1 is merged with the regular route after reshaping the regular route. The lesser demanded zone, which was previously served by the regular route is now served by a separate route with a low frequency.

4.9.7 Frequency of Feeder Routes

After finalizing the feeder routes and regular routes, the frequency of the routes can be determined.

In the SPS data collection, the departure times from the origins were recorded. From the data, following travel time patterns can be observed as in Table 30.

Table 30: Feeder Demand Fluctualtions in Time

	Departure time	Number of observations	Percentage distribution
1	07:00 a.m.	103	71%
2	11.00 a.m.	39	27%
3	03.00 p.m.	3	2%
		145	

Therefore, the demand for feeders can be identified to be distributed in a day similar to the distribution pattern in Table 30. Therefore, the identified demand for each feeder can be distributed, 71% from 7.00 a.m. – 11.00 a.m. and 27% from 11.00 a.m. – 3.00 p.m.

Taking a reasonable value as the capacity of a feeder bus, the frequency of buses in the Morning (7.00 a.m. – 11.00 a.m.), Noon (11.00 a.m. – 3.00 p.m.) and at evening (3.00 p.m. onwards can be calculated. This frequency assignment method can be followed for both design method 1 and 2.

For an example if the capacity of a feeder bus was taken as "n" passengers per bus, and the total demand for feeder bus route "A" is "D",

Then for morning 4 hours (7.00 a.m. – 11.00 a.m.),

Number of buses from 7.00 a.m. – 11.00 a.m. = (D*71%) / n

Therefore, for the morning period, for an hour, number of buses = (D*71%) / n / 4

For the noon period, Number of buses per hour = D*27% / n / 4

For the evening period, Number of buses per hour = D*2% / n / 4

Thereby, the frequency throughout the day can be identified for each feeder route. The number of buses is rounded up to the nearest value. Min number of buses per hour = 1

For an example, the feeder routes that connects to the Lumbini Temple LRT station were optimized and finalized in the previous step. The frequency assigning of each bus feeder route can be identified as the final step.

A sample feeder bus grid is shown in Figure 52. Assuming the capacity of a feeder bus = 60 passengers / bus, the bus frequency assignment conducted is shown in Table 31.

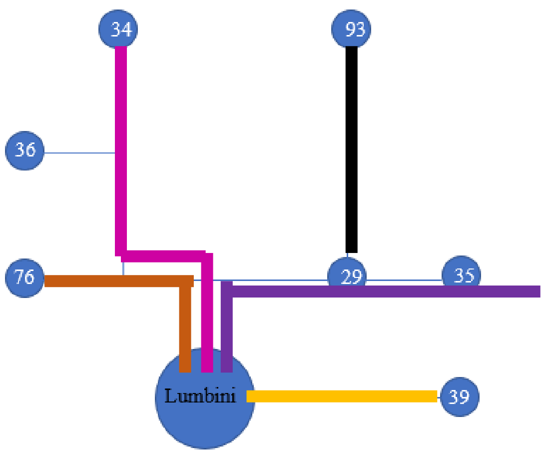


Figure 52: Feeder Bus Grid Connecting to Lumbini LRT

Table 31: Feeder Bus Frequency Assignment

Feeder Bus route	Morning (7.00 a.m. – 11.00 a.m.)	Noon (11.00 a.m. –3.00 p.m.)	Evening (3.00 p.m. onwards)
76 – LRT 1 route (Capacity = 1066)	4 buses/hr/dir Time headway = 15 minutes	2 bus/hr/dir Time headway = 30 minutes	1 bus/hr/dir Time headway = 60 minutes
35 – LRT 1 route (Capacity = 1090)	4 buses/hr/dir Time headway = 15 minutes	2 bus/hr/dir Time headway = 30 minutes	1 bus/hr/dir Time headway = 60 minutes
34 – LRT 1 route (Capacity =799)	3 buses/hr/dir Time headway = 20 minutes	1 buses/hr/dir Time headway = 60 minutes	1 buses/hr/dir Time headway = 60 minutes
39 – LRT 1 route (Capacity = 239)	1 buses/hr/dir Time headway = 60 minutes	1 buses/hr/dir Time headway = 60 minutes	1 buses/hr/dir Time headway = 60 minutes
98 – LRT 1 route (Capacity = 115)	1 buses/hr/dir Time headway = 60 minutes	1 buses/hr/dir Time headway = 60 minutes	1 buses/hr/dir Time headway = 60 minutes

In design method 1, a percentage of the demand for a feeder mode to connect to the LRT, is satisfied by the regular routes. In calculating frequency of feeders, only the demand satisfied by the feeder routes alone was considered. However, as the regular routes also supply for a certain feeder demand, the frequency of regular routes require changes as well.

To identify the new frequencies, the demand satisfied by each regular route will be identified and considering that added demand and the frequency that was assigned to the regular route previously, the new frequency will be defined.

5 Conclusions and Recommendations

The past literature was utilized to identify a methodology to develop a feeder bus network in the Sri Lankan context. In literature, certain special features were identified. In Sri Lanka, there are multiple literature on regional bus network development. Those literature are focused upon developing regional bus network which will cater to bus passengers to fulfill their requirement of trips between Origins and Destinations through the region. These studies do not consider the special case of feeder modes.

However, certain literature can be found from other countries where LRTs and other back bone transits such as BRT, Monorails, Rails are in operation. In those literatures, feeder bus network development and optimization are discussed. These identify the requirement of feeders, especially bus feeders for the optimum operation of the LRTs and other back bone transits.

As the aim of this study was to build a methodology to develop a feeder bus for a Light Railway Transit in Sri Lankan context, both the studies on the feeder bus network developments which are available in the context of other countries and the studies on regional bus planning in Sri Lankan context were combined to identify this methodology to develop a feeder bus for a Light Railway Transit in Sri Lanka.

The identified methodology is shown in Chapter 4. This methodology involves multiple steps which are discussed in the chapter.

The identified methodology was thereby applied for the Fort- Malabe LRT, which was proposed to be the first LRT to be implemented in Sri Lanka, requires a feeder network to connect potential catchment areas with the LRT. Identifying the catchment distances for different feeder modes was carried out using survey data and by service area approach method, the catchment areas for each feeder mode were identified.

By the calculations, the catchment distance and area for walking and cycling mode was identified as 800m and 13.92km^2 respectively. A catchment distance of 2.5km and a catchment area of 51.62 km^2 was calculated for private vehicles and taxi modes. Catchment area for the bus mode, was calculated to be 74.15 km^2 using the catchment distance of 3.3km. The values are shown in Table 32.

Table 32: Catchment Distances and Catchment Areas

Feeder Mode	***Catchment Distance***	***Catchment Area***
Walking and Cycling	800 m	13.92 km^2
Private vehicles and Taxi	2.5 km	51.62 km^2
Buses	3.3 km	74.99 km^2

After analyzing catchment area for each feeder mode, it was observed that the catchment area for mode walking and cycling can be further improved by allowing more pedestrian and cycling link connections over physical barriers. Catchment area of private vehicles and taxi was observed again limited due to the lack of connections. However, implementing new road link connections might not be practical due to the land use patterns and the lack of land availability. Walking and cycling, private and taxi catchment modes were not further analyzed in this study.

The focus of the study was the bus catchment for the LRT and the bus mode supplying the connection from the origins in the catchment to the nearest LRT station destinations. The population inside the potential bus catchment area (74.15 km^2) require bus route connections to reach the LRT station nearest to them from their residential origin. However, the number of routes and the road links that they occupy are limited and therefore, the potential bus catchment is not fully connected by the current bus network.

The existing bus network operating in the Fort – Malabe corridor was identified and data such as route number, stops, path, frequency, speed were collected and a data bundle of GTFS format was developed. From that data bundle, using the Conveyal analysis and assuming that passengers are willing to walk 400m to reach the nearest bus stop to board a bus to access the LRT station, the area that is supplied by the existing bus network was recorded. The passengers that have their origins located in this recorded area are connected with at least one bus route connecting to the nearest LRT by maximum 2 transfers. The area recorded was 40.28 km^2. The house-holds that are willing to use bus mode as their access mode to reach the LRT from their house-holds are under supplied currently.

Therefore, the study was proceeded to identify a design method, which will design a bus network in the LRT corridor, to provide connections to the households in the identified catchment area. The designed bus network was then optimized by route modifications and frequency assignment.

In designing the bus network for the LRT corridor, two design methods were followed. First design method was focused upon having the current bus network operating with a new supporting feeder network dedicated for LRT. The second design method that was followed was to implement a new feeder bus network design which will have the objective of feeding the LRT, disregarding the existing network. The transits between the OD pairs inside the catchment will be managed by transfers between the feeder routes and LRT.

The purpose of following two design methods was to consider the catchment area coverage and other factors such as resource availability, practicability of implementation, social impact of altering the bus network etc. of each design method in the context of the concerned corridor and identify the best suited design method.

In design method 1, the areas of the catchment, that are currently not supplied with a bus route, were considered, and feeder buses that will connect those areas were implemented to the system, where the regular buses are operating alongside the LRT. In design 1, the number of feeder buses that were applied for identified paths was 115. Those feeders are in addition to the regular buses operating in the corridor. The demand for feeders will be satisfied by the regular routes and the feeder routes both.

In second design, the catchment area of bus mode was taken as a whole and a feeder route was applied to each GND inside the area. 127 feeder routes were applied. The total of the feeder demand was deemed to be satisfied by the feeder routes. In design method 2, the goal was to rid the regular bus routes and implement a bus network with only feeder buses where all trips by public transit will be via feeder buses and the LRT.

The two design networks were both stimulated in the Conveyal analysis and for each LRT station the area that is accessible from, were taken, when each design was operating in the corridor with the LRT. By design method 1, the network supplied to an area of 62.15km^2, and in design 2, the coverage was 54.25km^2. In both designs, the coverage has improved significantly, where the coverage by existing network is only 40.2 km^2. By considering several factors, the design method 1 was selected as the method to proceed.

After the design was done, the network that was designed was further developed to be in the optimum condition. For an example, in the design, a feeder bus route was added for each GND division. However, in practical scenario, those bus routes are possible for optimization by procedures such as extending a regular route, merging with either a regular route or another feeder route, route breaking etc. The optimization process was done based on the demand of passengers reaching LRT in each GND. A network grid with road links as the links and GNDs as nodes were developed and demand occurred by each GND was added to the links that the feeder route connecting that GND travels on.

A rank was given to each feeder route that was previously assigned at the designing phase. The feeders were analyzed by going by the order of rank and decisions on route merging and breaking were taken based on the demand and length of the links. A guideline for decision making was proposed.

After finalizing the optimum feeder routes, the frequency was assigned to each of the feeder based on the surveyed time variation of demand. Where the merging or extending of a regular route was followed, the frequency of the route was decided by considering the frequency that the regular route was operating previously with the new added demand.

As a conclusion, it can be noticed that a procedure which is a combination of logical calculations and heuristic methods is suitable for feeder bus network design in Sri Lankan condition. For an example, the bus route path implementation can be done according to the shortest path condition and with the goal of maximizing the coverage. But in the feat of optimization, a heuristic approach can be followed.

In optimization, this study gives guidelines on how to make the decisions on route merging, breaking, reshaping etc. And in Sri Lankan conditions, the factors such as, availability of the resources can majorly affect the designer’s decision making as well. Therefore, the guidelines for route optimization may be followed with designer’s discretion on resource allocation.

As the final step, the frequency assignment for the routes was identified which is described in the process of application.

In the research following outcomes were generated.

- It was identified the catchment area criteria that was considered in CoMTrans study (Japan International Cooperation Agency, 2014) was not sufficient and requires further calculations.
- It was identified the travel times and distances preferred to be travelled by different access modes differ and thereby the catchment areas of the said access modes also differ.
- For all the access modes identified to be operated in the LRT corridor, catchment areas were calculated.
- The catchment areas were identified to be limited due to several reasons. The cause of limitation and mitigation efforts were discussed.
- Bus feeder mode was specially considered. The existing bus feeder coverage was identified.
- The road links in the bus feeder catchment area were identified along with their classifications of capacity and road width.
- New bus feeder links, which connects the origin GNDs with the LRT by the shortest path were trialed using a stimulation.
- Demand was estimated for the bus feeder for the links.
- Bus feeder links were optimized using techniques such as route addition, re-routing, merging etc. while giving priority to links in the hierarchy of demand, along with the frequency identification.
- The optimum condition and the methodology to generate the optimum feeder network was identified.

Furthermore, the recommendations can be implored. In the study only the fixed feeder routes are discussed. However, feeder routes can be improved to be demand responsive. Even though this study does not venture in to demand responsive feeder routes with flexible paths, it is an option that can be pursued to address the limited resources availability. However, for a demand responsive feeder network, the infrastructure, especially the information technology infrastructure will be crucial.

There are literature such as Tong, Zhou, Liu, & Zhou, 2017 and Narayan, Cats, van Oort, & Hoogendoorn, 2020 which discuss further on the demand responsive flexible feeder modes. They discuss on how the supply of feeder bus routes will vary with quantity and the type of demand.

For Sri Lanka, this may be not be a vialble option just yet as this will require the use of smart devices and a reliable information technology network. However, with the graduation of technology, flexible bus routes can be an optimum option for a transportation industry running on limited resources.

In the meantime, it can be further recommended the combination of flexible and fixed feeder routes to supply for a steady and varying demands both, which will also be suitable for current information technology structure in Sri Lanka.

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Annexures

Appendix A: JICA LRT preparatory survey report data: Travel modes and preferred travel time data for survey locations

	Time (min)																
	2	3	4	5	6	7	8	9	10	12	15	20	25	30	40	45	Total
Sebatian Canal									1		1						2
Walk / Bicycle											1						1
Bus									1								1
	Time (min)																
	2	3	4	5	6	7	8	9	10	12	15	20	25	30	40	45	Total
Fort									1								1
Walk / Bicycle									1								1
	Time (min)																
	2	3	4	5	6	7	8	9	10	12	15	20	25	30	40	45	Total
World Trade Center				2					1								3
Walk / Bicycle				2					1								3
	Time (min)																
	2	3	4	5	6	7	8	9	10	12	15	20	25	30	40	45	Total
Slave Island							1				1						2
Motorcycle (passenger)							1										1
Bus											1						1
	Time (min)																
	2	3	4	5	6	7	8	9	10	12	15	20	25	30	40	45	Total
Union Place									7								7
Walk / Bicycle									1								1
Motorcycle (passenger)									1								1
Taxi / Hired 3-Wheeler									2								2
Bus									3								3

	Time (min)																
	2	3	4	5	6	7	8	9	10	12	15	20	25	30	40	45	Total
Sethsiripaya	1	1		14		1	2		35		13	8	1	2			78
Walk / Bicycle				1		1			7		2						11
Private Car (driver)				1			2		6		2	1		1			13
Private Car (passenger)									2			3					5
Motorcycle (driver)	1	1		6					10		1	1					20
Motorcycle (passenger)									2								2
Taxi / Hired 3-Wheeler				3													3
Bus				3					7		8	3	1	1			23
Unknown									1								1
	Time (min)																
	2	3	4	5	6	7	8	9	10	12	15	20	25	30	40	45	Total
Lumbini Temple	2			13		3			28		5	4	1	1			57
Walk / Bicycle	2			4					8		3	1					18
Private Car (driver)				3		2			4								9
Private Car (passenger)				2					2								4
Private 3-Wheeler (passenger)									1								1
Motorcycle (driver)				3					4								7
Motorcycle (passenger)						1			3		1						5
Taxi / Hired 3-Wheeler									2								2
Bus				1					4		1	3	1	1			11

	Time (min)																
	2	3	4	5	6	7	8	9	10	12	15	20	25	30	40	45	Total
Talahena		2		10			2		20		8	3		2	1	2	50
Walk / Bicycle		1		5					4		4	1					15
Private Car (driver)		1		3			1		5							1	11
Private Car (passenger)				1					1							1	3
Private 3-Wheeler (driver)									1								1
Motorcycle (driver)				1			1		3		3						8
Motorcycle (passenger)									1								1
Bus									5		1	2		2	1		11
	Time (min)																
	2	3	4	5	6	7	8	9	10	12	15	20	25	30	40	45	Total
Cotta Road	1	2		10					21		4	4		1	1	1	45
Walk / Bicycle									14		2	2					18
Private Car (driver)				1													1
Private Car (passenger)		1		1													2
Private 3-Wheeler (driver)															1		1
Motorcycle (driver)		1		1					3								5
Motorcycle (passenger)				1					1		1	1					4
Taxi / Hired 3-Wheeler				4					1		1						6
Bus				2					2			1				1	6
Unknown	1													1			2

	Time (min)																
	2	3	4	5	6	7	8	9	10	12	15	20	25	30	40	45	Total
Welikada	1	2		22	3	5	6	1	30	1	18	7				1	97
Walk / Bicycle				4	3	4	5	1	11	1	5	2					36
Private Car (driver)				8					3			1					12
Private Car (passenger)									2								2
Private 3-Wheeler (driver)						1					1						2
Private 3-Wheeler (passenger)				2			1		1		4						8
Motorcycle (driver)		1		5					2		1						9
Motorcycle (passenger)		1		1					1		1						4
Taxi / Hired 3-Wheeler	1			2					1			1					5
Bus									9		5	3				1	18
Unknown											1						1

	Time (min)																
	2	3	4	5	6	7	8	9	10	12	15	20	25	30	40	45	Total
Malabe		1	1	33	1	3			39		20	6					104
Walk / Bicycle				11					11		6	1					29
Private Car (driver)				12	1	2			1		1						17
Private Car (passenger)			1									1					2
Private 3-Wheeler (driver)				2													2
Private 3-Wheeler (passenger)				2					2		4						8
Motorcycle (driver)		1		3		1			1								6
Motorcycle (passenger)									3		1						4
Taxi / Hired 3-Wheeler									6		1						7
Bus				3					15		7	4					29

	Time (min)																
	2	3	4	5	6	7	8	9	10	12	15	20	25	30	40	45	Total
Rajagiriya				1					1								2
Private Car (driver)				1													1
Private Car (passenger)									1								1
	Time (min)																
	2	3	4	5	6	7	8	9	10	12	15	20	25	30	40	45	Total
Battaramulla				5		1			6								12
Walk / Bicycle									1								1
Private Car (driver)				3		1			1								5
Private Car (passenger)				1					1								2
Private 3-Wheeler (driver)									1								1
Motorcycle (driver)									1								1
Unknown				1					1								2
	Time (min)																
	2	3	4	5	6	7	8	9	10	12	15	20	25	30	40	45	Total
Robert Gunawardana Mawatha				13		1			14		3						31
Walk / Bicycle				3					5								8
Private Car (driver)				1					3		1						5
Private Car (passenger)				1					1								2
Private 3-Wheeler (passenger)				1					1								2
Motorcycle (driver)				3					2								5
Motorcycle (passenger)				3		1			1		1						6
Taxi / Hired 3-Wheeler				1													1
Bus									1		1						2

	Time (min)																
	2	3	4	5	6	7	8	9	10	12	15	20	25	30	40	45	Total
Palan Thuna				6	1	2	1		21	1	6	1		1			40
Walk / Bicycle									3	1							4
Private Car (driver)				1	1				8								10
Private Car (passenger)				2			1		3								6
Motorcycle (driver)				1					1		1						3
Taxi / Hired 3-Wheeler				1		1					1	1					4
Bus						1			6		4			1			12
Unknown				1													1
	Time (min)																
	2	3	4	5	6	7	8	9	10	12	15	20	25	30	40	45	Total
Dayawanna Lake	1	1	1	11		5	1		7								27
Walk / Bicycle		1		2		2			1								6
Private Car (driver)				2		2	1		2								7
Private Car (passenger)			1	2					1								4
Private 3-Wheeler (driver)									1								1
Motorcycle (driver)	1			3		1											5
Motorcycle (passenger)				1													1
Bus									2								2
Unknown				1													1
	Time (min)																
	2	3	4	5	6	7	8	9	10	12	15	20	25	30	40	45	Total
Town Hall				3					1		1						5
Walk / Bicycle				1					1								2
Bus				2							1						3

	Time (min)																
	2	3	4	5	6	7	8	9	10	12	15	20	25	30	40	45	Total
Borella		1		1					2		1	1		1			7
Walk / Bicycle		1							1								2
Private Car (driver)									1								1
Bus				1							1	1		1			4
Grand Total	6	10	2	144	5	21	13	1	235	2	81	34	2	8	2	4	570

Appendix B: Comparison of Bus Network Catchment Area in Different Scenarios

			Existing bus network				Design Method 1 (regular + feeders)				Design Method 2 (feeders only)			
Zone_Code	Zone_Name	Shape_Area_Zone GND int bus catchment	Covered Area	Percentage of Covered Area	Uncovered area	Percentage Uncovered	Covered Area	Percentage of Covered Area	Uncovered area	Percentage Uncovered	Covered Area	Percentage of Covered Area	Uncovered area	Percentage Uncovered
1103030	Aluthmawatha	31,913	0	0	31,913	100	28,848	90	3,065	10	28,785	90	3,128	10
1103035	Lunupokuna	402,429	17,035	4	385,394	96	361,106	90	41,322	10	220,415	55	182,014	45
1103040	Bloemendhal	348,795	0	0	348,795	100	347,963	100	832	0	293,499	84	55,296	16
1103045	Kotahena East	373,788	170,962	46	202,826	54	373,788	100	0	0	354,729	95	19,059	5
1103050	Kotahena West	334,877	191,958	57	142,918	43	334,877	100	0	0	325,115	97	9,762	3
1103055	Kochchikade North	270,780	132,623	49	138,157	51	265,592	98	5,189	2	265,589	98	5,191	2
1103060	Jinthupitiya	201,679	78,106	39	123,573	61	201,679	100	0	0	201,679	100	0	0
1103065	Massangasweediya	260,744	45,829	18	214,915	82	260,744	100	0	0	260,744	100	0	0
1103070	New Bazaar	507,682	456,190	90	51,492	10	507,682	100	0	0	507,682	100	0	0
1103075	Grandpass South	589,007	230,668	39	358,339	61	589,007	100	0	0	550,026	93	38,981	7
1103080	Grandpass North	232,235	18,532	8	213,702	92	232,235	100	0	0	153,755	66	78,479	34
1103085	Nawagampura	2,923	0	0	2,923	100	2,923	100	0	0	2,923	100	0	0
1103090	Maligawatta East	638,112	507,952	80	130,160	20	638,112	100	0	0	551,949	86	86,163	14
1103095	Khettarama	279,750	210,002	75	69,749	25	279,750	100	0	0	279,750	100	0	0
1103100	Aluthkade East	281,112	229,311	82	51,801	18	281,112	100	0	0	281,112	100	0	0
1103105	Aluthkade West	148,938	94,319	63	54,618	37	148,938	100	0	0	148,938	100	0	0
1103110	Kochchikade South	228,335	228,335	100	0	0	228,335	100	0	0	228,335	100	0	0
1103115	Pettah	890,081	814,984	92	75,097	8	873,732	98	16,349	2	787,814	89	102,268	11
1103120	Fort	1,056,479	513,629	49	542,851	51	565,021	53	491,458	47	500,385	47	556,094	53
1103125	Galle Face	391,626	331,103	85	60,523	15	331,103	85	60,523	15	301,172	77	90,453	23
1103130	Slave Island	113,471	113,471	100	0	0	113,471	100	0	0	113,471	100	0	0
1103135	Hunupitiya	767,061	745,026	97	22,035	3	761,231	99	5,830	1	604,159	79	162,903	21
1103140	Suduwella	607,157	560,582	92	46,575	8	600,694	99	6,463	1	552,759	91	54,398	9
1103145	Keselwatta	309,140	302,795	98	6,345	2	309,140	100	0	0	309,140	100	0	0
1103150	Panchikawatta	242,232	242,232	100	0	0	242,232	100	0	0	242,232	100	0	0
1103155	Maligawatta West	260,998	200,870	77	60,127	23	260,998	100	0	0	239,572	92	21,425	8
1103160	Maligakanda	240,965	240,965	100	0	0	240,965	100	0	0	230,595	96	10,370	4
1103165	Maradana	252,144	252,144	100	0	0	252,144	100	0	0	252,144	100	0	0
1103170	Ibbanwala	359,414	359,414	100	0	0	359,414	100	0	0	359,414	100	0	0
1103175	Wekanda	574,278	566,631	99	7,647	1	574,278	100	0	0	559,507	97	14,771	3
1106030	Orugodawatta	38,961	36,941	95	2,020	5	38,447	99	514	1	38,441	99	520	1
1106035	Meethotamulla	310,936	137,377	44	173,559	56	310,936	100	0	0	310,936	100	0	0
1106105	Kuriniyawatta	26,744	0	0	26,744	100	26,744	100	0	0	26,744	100	0	0
1106110	Kolonnawa	211,171	116,663	55	94,508	45	211,171	100	0	0	211,108	100	62	0
1106115	Dahampura	52,055	431	1	51,624	99	52,055	100	0	0	52,055	100	0	0
1106120	Singhapura	82,014	11,962	15	70,053	85	82,014	100	0	0	80,138	98	1,876	2
1106145	Mulleriyawa South	195,371	0	0	195,371	100	191,276	98	4,095	2	125,381	64	69,990	36
1106150	Malgama	128,107	0	0	128,107	100	106,537	83	21,570	17	115,176	90	12,932	10
1106155	Udumulla North	102,666	0	0	102,666	100	59,635	58	43,031	42	37,318	36	65,348	64
1106160	Maligagodella	351,028	0	0	351,028	100	208,488	59	142,540	41	143,065	41	207,963	59
1106165	Rajasinghagama	1,834,952	0	0	1,834,952	100	1,009,551	55	825,401	45	1,217,336	66	617,616	34
1106170	Udumulla South	420,347	34,935	8	385,412	92	420,347	100	0	0	419,172	100	1,175	0

			Existing bus network				Design Method 1 (regular + feeders)				Design Method 2 (feeders only)			
Zone_Code	Zone_Name	Shape_Area_Zone GND int bus catchment	Covered Area	Percentage of Covered Area	Uncovered area	Percentage Uncovered	Covered Area	Percentage of Covered Area	Uncovered area	Percentage Uncovered	Covered Area	Percentage of Covered Area	Uncovered area	Percentage Uncovered
1106175	Himbutana East	626,573	0	0	626,573	100	578,813	92	47,760	8	374,068	60	252,505	40
1106180	Himbutana West	458,741	0	0	458,741	100	384,266	84	74,475	16	110,809	24	347,932	76
1106185	Malpura	287,902	59,731	21	228,171	79	282,062	98	5,841	2	208,280	72	79,622	28
1106190	Gothatuwa New Town	131,061	117,708	90	13,353	10	131,061	100	0	0	126,723	97	4,338	3
1106195	Kajugahawatta	67,315	22,999	34	44,317	66	67,315	100	0	0	64,685	96	2,631	4
1106200	Gothatuwa	23,948	0	0	23,948	100	4,762	20	19,186	80	4,607	19	19,341	81
1106205	Salamulla	221,434	0	0	221,434	100	204,655	92	16,780	8	191,768	87	29,667	13
1106210	Wijayapura	224,909	11,434	5	213,476	95	141,807	63	83,102	37	141,479	63	83,430	37
1106215	Gajabapura	442,358	192,921	44	249,438	56	289,553	65	152,805	35	288,904	65	153,454	35
1106220	Madinnagoda	624,467	62,223	10	562,244	90	425,956	68	198,511	32	412,519	66	211,948	34
1106225	Elhena	230,573	100,991	44	129,582	56	226,308	98	4,265	2	226,126	98	4,447	2
1106230	Dodamgahahena	243,161	243,161	100	0	0	243,161	100	0	0	243,161	100	0	0
1109005	Welivita	52,895	0	0	52,895	100	52,895	100	0	0	52,895	100	0	0
1109010	Raggahawatta	144,176	0	0	144,176	100	75,590	52	68,586	48	75,576	52	68,599	48
1109015	Hewagama	220,613	137,290	62	83,323	38	119,016	54	101,597	46	41,675	19	178,938	81
1109020	Kaduwela	20,175	20,175	100	0	0	20,175	100	0	0	20,175	100	0	0
1109055	Kothalawala	1,321,191	792,311	60	528,880	40	769,049	58	552,142	42	756,744	57	564,447	43
1109060	Mahadeniya	1,949,383	0	0	1,949,383	100	1,081,464	55	867,919	45	1,228,922	63	720,460	37
1109065	Thalahena North	694,212	42,898	6	651,313	94	640,719	92	53,492	8	584,681	84	109,530	16
1109070	Malabe North	2,032,337	1,177,763	58	854,575	42	1,302,436	64	729,902	36	1,195,972	59	836,365	41
1109075	Thunadahena	851,664	0	0	851,664	100	180,660	21	671,004	79	283,952	33	567,712	67
1109120	Pore	13,881	0	0	13,881	100	0	0	13,881	100	961	7	12,920	93
1109125	Malabe East	2,182,762	524,224	24	1,658,537	76	1,726,730	79	456,032	21	1,293,034	59	889,728	41
1109130	Malabe West	1,529,149	1,407,019	92	122,130	8	1,465,290	96	63,859	4	1,190,289	78	338,860	22
1109135	Thalangama North B	874,950	683,471	78	191,479	22	785,546	90	89,405	10	775,516	89	99,435	11
1109140	Thalahena South	574,181	333,138	58	241,044	42	564,654	98	9,527	2	564,563	98	9,618	2
1109145	Muttettugoda	1,046,802	574,403	55	472,400	45	947,797	91	99,005	9	809,460	77	237,343	23
1109150	Thalangama North A	2,012,666	1,175,299	58	837,367	42	1,881,227	93	131,439	7	1,439,622	72	573,044	28
1109155	Walpola	1,507,788	85,997	6	1,421,791	94	1,275,893	85	231,896	15	866,904	57	640,884	43
1109160	Kalapaluwawa	961,312	678,216	71	283,096	29	896,653	93	64,659	7	665,020	69	296,293	31
1109165	Kotuwegoda	636,564	601,222	94	35,341	6	491,116	77	145,447	23	491,395	77	145,169	23
1109170	Subhoothipura	941,788	664,569	71	277,219	29	626,532	67	315,256	33	662,814	70	278,975	30
1109175	Udumulla	412,926	118,947	29	293,979	71	234,433	57	178,493	43	194,499	47	218,427	53
1109180	Battaramulla North	580,788	580,788	100	0	0	580,788	100	0	0	547,598	94	33,190	6
1109185	Batapotha	1,270,918	530,598	42	740,320	58	1,269,808	100	1,110	0	1,031,852	81	239,066	19
1109190	Pothuarawa	1,831,530	84,979	5	1,746,551	95	1,277,185	70	554,345	30	1,118,976	61	712,554	39
1109195	Hokandara North	1,785,213	821,190	46	964,023	54	1,620,892	91	164,321	9	888,403	50	896,810	50
1109220	Hokandara South	2,885	2,885	100	0	0	2,885	100	0	0	2,885	100	0	0
1109225	Arangala	1,001,946	876,535	87	125,411	13	1,001,946	100	0	0	747,447	75	254,499	25
1109230	Evarihena	242,661	7,139	3	235,522	97	7,414	3	235,246	97	3	0	242,658	100
1109235	Kumaragewatta	1,843,131	541,397	29	1,301,733	71	1,232,468	67	610,662	33	1,039,197	56	803,934	44
1109240	Jayawadanagama	373,406	0	0	373,406	100	298,573	80	74,833	20	206,677	55	166,730	45

			Existing bus network				Design Method 1 (regular + feeders)				Design Method 2 (feeders only)			
Zone_Code	Zone_Name	Shape_Area_Zone GND int bus catchment	Covered Area	Percentage of Covered Area	Uncovered area	Percentage Uncovered	Covered Area	Percentage of Covered Area	Uncovered area	Percentage Uncovered	Covered Area	Percentage of Covered Area	Uncovered area	Percentage Uncovered
1109245	Aruppitiya	623,913	231,193	37	392,721	63	623,913	100	0	0	623,913	100	0	0
1109250	Asiri Uyana	501,055	455,721	91	45,334	9	501,055	100	0	0	501,055	100	0	0
1109255	Battaramulla South	518,233	218,432	42	299,801	58	246,704	48	271,529	52	411,975	79	106,259	21
1109260	Rajamalwatta	690,142	590,735	86	99,408	14	663,175	96	26,967	4	595,379	86	94,763	14
1109265	Pahalawela	1,092,687	160,592	15	932,095	85	784,902	72	307,785	28	646,642	59	446,045	41
1109270	Wickramasinghapura	341,432	93,719	27	247,713	73	310,269	91	31,164	9	202,930	59	138,502	41
1109280	Hokandara East	111,144	80,818	73	30,326	27	87,979	79	23,165	21	41,926	38	69,218	62
1121020	Thalawathugoda West	52,144	0	0	52,144	100	34,955	67	17,189	33	30,376	58	21,768	42
1121025	Thalawathugoda East	48,410	15,187	31	33,223	69	48,410	100	0	0	48,183	100	227	0
1124005	Obesekarapura	582,023	112,310	19	469,713	81	527,323	91	54,701	9	495,963	85	86,060	15
1124010	Welikada West	498,447	121,516	24	376,931	76	498,447	100	0	0	492,649	99	5,798	1
1124015	Welikada East	1,072,336	679,526	63	392,810	37	1,000,499	93	71,837	7	844,302	79	228,034	21
1124020	Rajagiriya	669,576	654,348	98	15,228	2	638,342	95	31,234	5	638,505	95	31,071	5
1124025	Welikada North	299,601	270,579	90	29,022	10	253,828	85	45,773	15	215,816	72	83,785	28
1124030	Nawala East	977,605	750,377	77	227,228	23	707,600	72	270,005	28	588,477	60	389,128	40
1124035	Koswatta	856,677	660,247	77	196,430	23	794,134	93	62,543	7	739,525	86	117,152	14
1124040	Ethulkotte West	478,967	161,817	34	317,150	66	463,925	97	15,041	3	401,875	84	77,092	16
1124045	Ethulkotte	932,716	793,633	85	139,083	15	931,867	100	850	0	799,309	86	133,407	14
1124050	Pitakotte East	627,179	177,651	28	449,528	72	457,138	73	170,041	27	226,887	36	400,293	64
1124055	Pitakotte	402,772	402,635	100	137	0	401,622	100	1,150	0	307,604	76	95,168	24
1124060	Pitakotte West	340,935	92,365	27	248,570	73	51,237	15	289,698	85	29,168	9	311,767	91
1124065	Nawala West	955,096	151,327	16	803,770	84	434,433	45	520,663	55	387,602	41	567,494	59
1124070	Nugegoda West	202	200	99	2	1	202	100	0	0	202	100	0	0
1124075	Pagoda	34,076	0	0	34,076	100	0	0	34,076	100	0	0	34,076	100
1127005	Kollupitiya	593,473	583,144	98	10,329	2	593,309	100	163	0	466,338	79	127,135	21
1127010	Bambalapitiya	1,034,010	931,885	90	102,126	10	1,034,010	100	0	0	953,658	92	80,353	8
1127016	Kurunduwatta 1	345,919	345,919	100	0	0	345,919	100	0	0	345,919	100	0	0
1127017	Kurunduwatta 2	1,098,091	1,098,091	100	0	0	1,098,091	100	0	0	1,070,253	97	27,838	3
1127018	Kurunduwatta 3	714,987	690,102	97	24,885	3	547,380	77	167,607	23	575,377	80	139,610	20
1127019	Kurunduwatta 4	1,407,789	1,395,530	99	12,259	1	1,407,789	100	0	0	1,407,789	100	0	0
1127020	Kuppiyawatta West	371,060	371,060	100	0	0	371,060	100	0	0	371,060	100	0	0
1127025	Kuppiyawatta East	579,079	541,821	94	37,257	6	579,079	100	0	0	443,674	77	135,404	23
1127030	Dematagoda	726,341	715,654	99	10,687	1	726,341	100	0	0	656,868	90	69,473	10
1127035	Wanathamulla	624,518	538,818	86	85,701	14	538,152	86	86,366	14	384,208	62	240,310	38
1127040	Borella North	975,121	851,705	87	123,417	13	805,020	83	170,102	17	709,278	73	265,844	27
1127045	Borella South	680,491	680,491	100	0	0	680,491	100	0	0	680,491	100	0	0
1127050	Gothamipura	1,070,482	950,418	89	120,063	11	1,013,281	95	57,200	5	903,287	84	167,195	16
1127055	Narahenpita	659,525	527,133	80	132,392	20	513,897	78	145,628	22	524,164	79	135,361	21
1127061	Thimbirigasyaya 1	711,770	473,566	67	238,203	33	711,770	100	0	0	487,208	68	224,561	32
1127062	Thimbirigasyaya 2	1,013,269	623,070	61	390,199	39	813,716	80	199,553	20	818,208	81	195,061	19
1127065	Milagiriya	214,586	194,936	91	19,650	9	214,586	100	0	0	159,687	74	54,899	26
1127070	Havelock Town	11,847	11,847	100	0	0	11,847	100	0	0	193	2	11,654	98
1127075	Kirula	1,151,377	356,448	31	794,930	69	979,715	85	171,662	15	362,431	31	788,946	69
1127080	Kirulapone	8,000	551	7	7,449	93	8,000	100	0	0	1,666	21	6,334	79