TELETRAFFIC IN THE KENYAN NETWORK - OVERVIEW ASSESSMENT AND FORECAST

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This thesis is my original work and has not been presented for a degree in any other University.

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This thesis has been submitted for examination with my approval as a University supervisor.

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ABSTRACT

A telecommunications network is an orderly, economical arrangement of telecommunications plant which allows the transmission of information by electrical means. Two objectives of any network are to provide a good grade of service and to avail service to new users with minimal delay.

This thesis gives an overview of the Kenyan Telecommunications network and introduces its structure and the services it offers. By subdividing the network into smaller networks evolved around the major towns, the extent to which the network objectives are met is assessed. A simple systematic method of obtaining forecasts on future service demands is presented.

The estimates of the offered grades of service show that 24% of the links connecting automatic switching systems offer worse grades of service than the designed numerical value.

Further results show that for the automated network around the major towns in Kenya the demand for telecommunications service has not been met. A significant percentage of what is considered

'total demand' is contributed by waiting users. The fact that this unsatisfied demand figure tends to increase with time leads to the conclusion that demand forecasts ma y have not always been reliable.

The methods deviced in this thesis would be useful for telecommunications organizations whose developing networks do not incorporate advanced network management facilities.

CONTENTS

LIST OF ABBREVIATIONS AND SYMBOLS

V	Volume of traffic
I(t)	Traffic Intensity at time t
A	Traffic intensity in Erlangs
A_o	Offered traffic intensity in erlangs
A_c	Carried traffic intensity in erlangs
E	Time congestion
B	Call congestion
NSC	National Switching Centre
ASC	Area Switching Centre
GSC	Group Switching Centre
EO	End Office
RS.	Rotary Switch
C	Number of meter operations
N	Number of Scans
S	'Send' Signalling wire
R	'Receive' Signalling wire
GOS	Grade of service
n	Number of circuits in a route
N(t);y	Demand
R(t);A2	Growth rate
k	Saturation value for Logistic growth curve
MFC	Multi-Frequency Compelled

CHAPTER ONE

INTRODUCTION

The first stage in the development of any area is the provision of a complete infrastructure including power, water and communication. Telecommunication service is an essential tool in the achievement of development.

In Kenya the provision of telecommunications services is a monopoly of the Kenya Posts and Telecommunications Corporation (KP & TC), whose telecommunications network can be considered as one of the more advanced in Africa. It offers a variety of services such as telephone services, telex services, data transmission services and facsimile services. International Subscriber Dialling services have been recently introduced. Systems employing latest technologies are incorporated in the network such as digital microwave radio systems and PCM systems on cable. Future plans include the introduction of digital public switching systems, optical fibre transmission systems as well as public land mobile telephone services.

A network such as this has the objective of providing services to the satisfaction of the public.

However, it is not uncommon to hear complaints, for example "I applied for a telephone two years ago and have not been served to date" or "In the morning hours it is impossible to call a number in Kisumu from Nairobi".

In advanced networks employing digital techniques, incorporated network management facilities perform continuous traffic observation duties to monitor traffic flow characteristics. The Kenyan network is predominantly analogue and relies on manually collected and processed data for its network management. Traffic Tables derived from similar tables previously used in other (developed) countries, particularly Japan and Sweden are used when observing and processing teletraffic data. However in some cases these methods and tables may not appropriately represent the Kenyan network status as calling habits are dictated to a large extent by culture, and differ from country to country. As an example, in Kenya it is observed that the holding times are much longer than those observed in developed countries. This is because whereas, for example, the Japanese use the telephone for short messages, Kenyans have a tendency to hold long social conversations on the telephone. In Kenya a business conversation only begins after words of greetings and enquiries about the family!

Demand forecasting is performed in two categories:-

- forecasting in new areas where service is to be introduced
- forecasting for growth in areas already having service.

In the first case a physical survey of the area to be served is done, where personnel travel from house to house enquiring from the inhabitants whether or not telephone service would be required. In addition building types are graded into those likely and those not likely to require service.
In the second case it has been the practice to forecast demand by judgement. By looking at the connected users' figures and the figures of the unsatisfied demand in an area, a forecast of future demands is made intuitively. The guideline for the forecaster is that the unsatisfied demand figure should reduce while the connected lines should increase. This method is dependent on the experience of the forecaster and may sometimes result in an ill-dimensioned route.

This thesis is an attempt to explain why for example the time lag between application for and provision of service is sometimes long. It gives reasons why it is difficult to communicate between some points in the network and identifies those points.

Simple techniques of teletraffic data processing are evolved. In particular a simple programme to derive estimates of the blocking encountered on transmission links is developed.

Also a procedure for estimating demand forecasts is established. This procedure depends on a sound data base and is not dependent on the individual forecaster, and is thus more reliable.

CHAPTER TWO

AN OVERVIEW OF THE KENYA TELECOMMUNICATIONS NETWORK

2.1 Telecommunications Network

The object of a telecommunications system is to transmit information by electrical means between points connected on it. A permanent connection provided between each terminal to every other terminal in the system would not only be prohibitively expensive, but would result in a lot of confusion caused by the large number of wires that would have to be used. To avoid this expense and confusion it is found necessary to provide common switching points to which terminals are connected each by a pair of wires; and to interconnect these common switching points by interexchange links and transit switching points. This arrangement constitutes a telecommunications network.

A telecommunications network is thus defined as a method of connecting switching points so that any terminal can communicate with any other terminal. Basically the network can be decomposed into two parts.

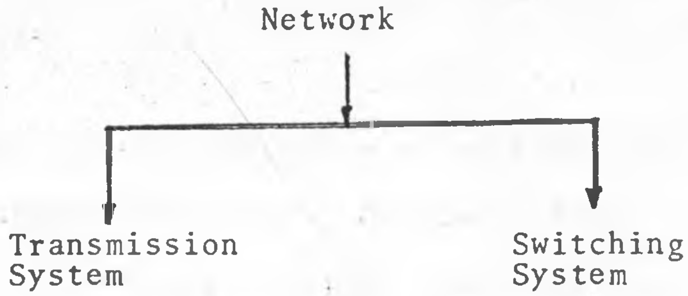

Figure 2.1: Telecommunications Network

The ideal transmission system allows any two users (connected to any two terminals) to communicate satisfactorily, while the switching systems permit economical building of the network by concentration of transmission facilities. Viewed in this way the network can be illustrated as a system of nodes interconnected by links. The nodes represent switching systems; and the links represent circuit groups which carry traffic between the nodes. Each node can act as a traffic source, a traffic sink or a transit point, and a link may either be unidirectional or bidirectional.

2.1.1 Network Configurations

By way of introduction consider a case where users have access to the network by a local switching system (or node) to which they are connected. The problem to be solved then is that of interconnecting all these nodes to allow communication between each user to any other user at minimum cost, with maximum efficiency. Basically there are two methods of interconnection that can be devised:-

- mesh connection
- star connection

2.1.2 Mesh Configuration

In mesh connection every node in the system is connected to every other node by a direct link.

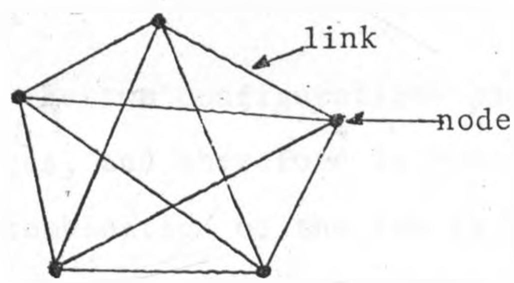

Figure 2.2: Mesh Configuration

With this configuration the number of links 'L' is related to the number of nodes 'n' by the equation

$$L = n(n-1)/2$$

2.1.3 Star Configuration

A star connection utilizes an intervening (transit) point T so that each node in the system is interconnected to any other via this transit switch.

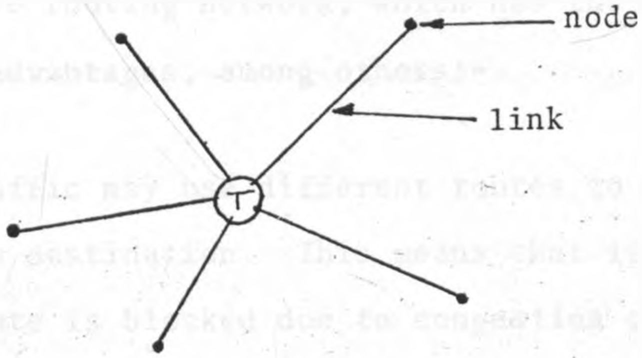

Figure 2.3: Star Configuration

In this configuration the number of nodes equals the number of links.

$$L = n$$

Each of the two configurations have advantages and disadvantages, and therefore in practice a compromise or combination of the two is used. Consider for example a fully star connected network. Failure of the transit switching system T would mean no communication between the nodes. In a mesh network however failure of one switching system would not cause total communications failure as the other nodes can still communicate. Further to this a link failure in a mesh network does not necessarily cut off the affected node as communication can be effected using alternative links.

The resulting network, built as a combination of star and mesh configurations constitutes an alternative routing network, which has the following specific advantages, among others:-

1) Traffic may use different routes to get to its destination. This means that if one route is blocked due to congestion or failure an alternative route can be used, and thus no traffic is 'lost'.

2) The efficiency of the network is enhanced since the traffic is first offered to direct high usage routes and the overflows directed to alternative routes. These alternative routes carry traffic from many origins and are therefore also utilized efficiently.

3) There is a trade off on costs where direct routes can save on the transit switching equipment costs.

2.1.4. Heirarchical Network

In order to reduce the number of links to a reasonable value and also permit efficient handling of high traffic intensities on busy routes and overflows a heirarchical network is called for. A heirarchical network has levels of importance of exchanges which constitute the network. A switching system depends on the next (higher) order system in the heirarchy to enter the network. There are two connection methods that can be adopted by automatic switching systems namely:-

direct connecting method
indirect connecting method.

In the direct connecting method the switching equipment responds to the respective digits dialled by the caller, operates in sequence to locate the called terminal and establish the connection as soon as the last digit is dialled. In the indirect connecting method the equipment receives and memorizes all dialled digits, and converts these digital codes into other codes necessary for the identification of the called terminal. The connection of the path is then performed by the switch.

2.2 Switching Systems

Having briefly discussed the telecommunications network as a whole a closer look at the switching part of the network follows with particular reference to the switching systems in the Kenyan network, to give an overview and appreciation of the basic concepts of telecommunication switching.

The important point of the switching operation is to select desired equipment and connect the calling party to the desired party. Lines connected to one switching point (node) are divided into two groups: Inlet group and outlet group. In the inlet group calls are originated by users, who declare their intention for speech. An originated call from the inlet group is connected to the outlet group which is divided into several indepedent sections, each serving a similar purpose.

Telephone switching systems are classified into two groups: manual switching systems and automatic switching systems. The basic functions are common to both system groups; with connections being completed by operators in manual systems while in the automatic systems the connections are automatically established by the switching equipment.

2.2.1 Basic functions of a Switching System

There are eight basic functions of a switching system necessary to achieve switching operation as discussed above:-

1. Alerting
2. Attending
3. Control

4. Information receiving
5. Busy testing
6. Interconnecting
7. Information transmitting
8. Supervisory.

When a user seeks to establish a link for communication the switching system is alerted (1). There has to be some communication from the switching system to the user to the effect that the request for the establishment of a link is being attended to (2). The user then gives information as to which other point in the network he requires to communicate with. This information is received by the switch; which then tests for the possibility of establishing the connection; and informs the caller if the connection cannot be established. One of the reasons leading to failure of a required connection is a busy link encountered along the path of connection. Thus this condition must be tested by the switching system; and if the busy test is negative the system goes ahead to make the required connection and informs the calling user that the connection has been made successfully. The required link for speech having been thus established the calling party communicates with the required party.

The duties performed by the switching system do not end at this point; for it must supervise the established connection such that when the use of the established link is completed it can release all the connections; thus rendering the path free for use by other callers.

2.2.2 Functional Elements of the Switching System

In order to perform the functions outlined above efficiently the switching system has necessarily three functional elements:-

- Concentration
- Distribution
- Expansion.

The concentration stage reduces the number of switching paths and trunks.
In the distribution stage traffic is channeled to the respective routes.
The expansion stage allows access to incoming circuits for all the users connected to the terminals efficiently.

For illustrative purposes consider a switching system as having originating-line appearances, where callers requiring to be connected are accessed; and terminating-line appearances where users to whom communication is required are accessed. This idea is illustrated in Fig. 2.4. below

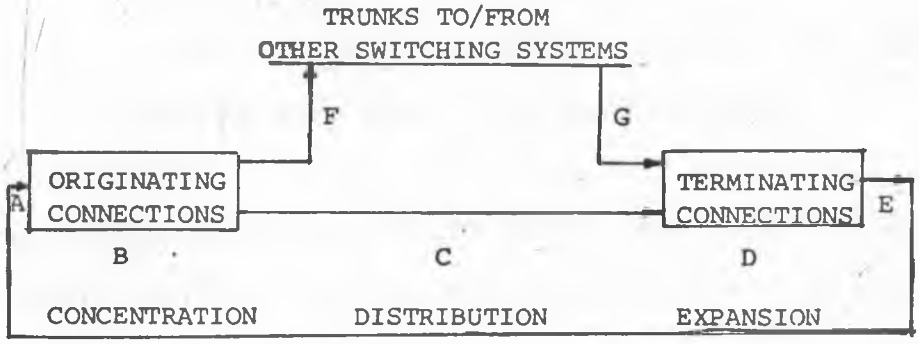

Figure 2.4: Functional Elements of a Switching System

For any local switching system there are three different call possibilities, namely:-

a) Intra-system call where a caller connected on the switching system wishes to communicate with another user also connected to the same system. The routes used in this type of call are

$$A \rightarrow B \rightarrow C \rightarrow D \rightarrow E.$$

b) Outgoing connection where an originating caller connected on the switching system wishes to communicate with another user connected on a different local switch. The routes required in this kind of connection are $A \rightarrow B \rightarrow F$

c) Incoming connection where it is required to communicate with a user on a local switch, from a distant switching system. The relevant routes here are G ⟶ D ⟶ E.

Call concentration occurs at B and call expansion takes place at D; whereas distribution takes place at C in this illustration.

2.3 Switching Systems in the Kenyan Network

In the Kenyan network both manual and automatic switching systemsexist. From an approximate 90,000 users (telephone connections) approximately 78,000 are connected to automatic exchanges and 12,000 connected to manual exchanges. This represents 87%.of the total connection being served by automatic systems and 13% being served by manual boards.

The automatic switching systems are of two main types, namely the Strowger step-by-step electromechanical exchange and the Hitachi Cross-bar electromechanical exchanges. However the step-by-step systems are old and relatively few; and are earmarked for replacement by the next generation of switching systems in the near future.

The manual exchanges in existence in the network are of two capacities; one being a 70-line magneto switchboard and the other a 100-line magneto switchboard. These two switchboards form the building blocks of manual exchanges as for example two 70-line switchboards can be combined to serve 140 users; or where 400 users are to be served four 100-line switchboardscan be used. Generally manual exchanges are provided in remote locations where the demand for telephone service is below 500 users. They are linked to 'parent' exchanges which are normally automatic exchanges, and depend on these 'parent' exchanges for access to the rest of the network.

Following is a brief description of the switching operation in each of these exchange types.

2.3.1 Manual Exchanges

In a typical manual switching centre the operator performs all of the eight switching functions. The interconnecting function is done via jacks which appear in front of the operator. There are jacks for users lines and jacks for outgoing and incoming circuits or trunks, which link the switch to other distant exchanges. These jacks are interconnected by use of connection cords. The number of connection cords is always less than half the number of jacks; and the concentration stage is thus accomplished at this point. Distribution is also considered to take place at this point since any cord may be used to complete a connection to any of the terminating jacks. The attending-alerting functions are accomplished as follows: A user alerts the exchange by generating a 17 Hz sinusoidal signal from his receiver instrument set. This signal causes a mechanical indicator to drop, thus drawing the attention of the operator to the demand for service.

Next the operator assumes the control function determining which connection cords are idle; using one of these idle cords to speak to the calling user; obtaining information from the caller regarding the party with which a connection is sought, determining which outgoing jack should be used; testing the selected link for busy condition and eventually making the connection. The called party is allerted by a signal which rings his telephone instrument bell; and a communication channel is thus established. The operator supervises the connection and releases all the equipment when the communication is terminated.

2.3.2 Step-by-step Electromechanical Exchange

The few step-by-step exchanges still in existence in the Kenyan network are situated in Nairobi, Mombasa, Nakuru and Kisumu.

A step-by-step exchange is based on rotary or two-motion switches each provided with an exclusively used control circuit. These control circuits control vertical or horizontal motion upon receipt of dial pulses. Each two-motion switch has 10 levels. In its simplest form dial pulses from the users' telephone activate the switch, with each pulse causing the switch to step by one level. The step-by-step exchange therefore adopts the direct connecting method.

2.3.3 Crossbar Switching Systems

The crossbar is a matrix switch used to establish a speech path under common control equipment. Common control is here defined as providing a means of control of the interconnecting switch network, first identifying the input and output terminals of the network that are free and then establishing a path between them.

In this section the operation of the Hitachi crossbar exchange will be outlined. However it must be pointed out that there are other types of crossbar exchanges in the network which will not be discussed as they exist in negligible numbers.

Figure 2.5 Shows the arrangement of the whole crossbar exchange.

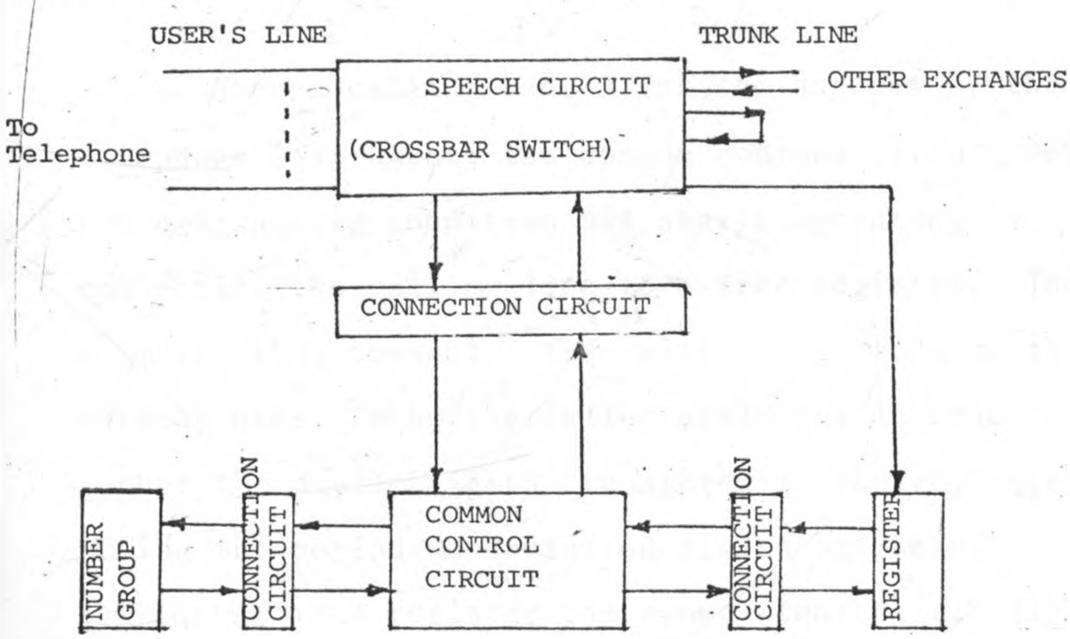

Figure 2.5: Crossbar Exchange

The speech circuit is a crossbar switch network where the switching operation is performed. The register is a circuit which memorizes digits received by it. The number group is a translation circuit which determines the corresponding terminal location from a dialed number.

The connection circuits perform inter-equipment connections for individual steps of the switching operation. In the crossbar switching system the control circuits are centralized in one section which makes it possible to have uniform control operation for the whole switching system. A description of the control operations performed by the common control circuit follows.

When a calling user lifts the handset of the telephone instrument, the common control circuit detects the originating condition and starts operating by connecting the calling line to a free register. The register thus connected transmits a dial tone to the calling user. When the caller dials the desired number the dialled digits are stored in the register. During the period when dialled digits are being transmitted to the register the common control circuit is released from the calling line and is free to serve other calling users. The common control circuit is seized again as soon as the number of digits required for the connection have been stored in the register. The common control circuit identifies the desired line based upon the received digits, using the number group (translation circuit) and performs the required connection operations on the crossbar switch network.

2.4 The Kenyan Telecommunications Network Heirarchy

Figure 2.6 is a representation of the portion of the Kenyan network in which the traffic data processed in this project was obtained. On it is represented the automatic switching systems of the crossbar types (as nodes) and the circuit groups (links) connecting the switches. It is basically a heirarchial network with the lowest ranking switch designated 'end office' and the highest ranking switch known as the national switching centre. (see Fig. 2.6a).

There is one National switching centre situated in Nairobi, which also performs the duties of an area switching centre for Nairobi. Other area switching centres are situated in Nyeri, Kisumu and Nakuru. In Mombasa a group switching centre performs the functions of an area switching centre for the area. The other group switching centres are situated in major towns such as Kericho, Eldoret, Kakamega, Malindi, Machakos, Athi River, Thika, Nanyuki, Muranga, Nyeri, Meru and Embu.

Figure 2.6: Kenyan Telecommunic

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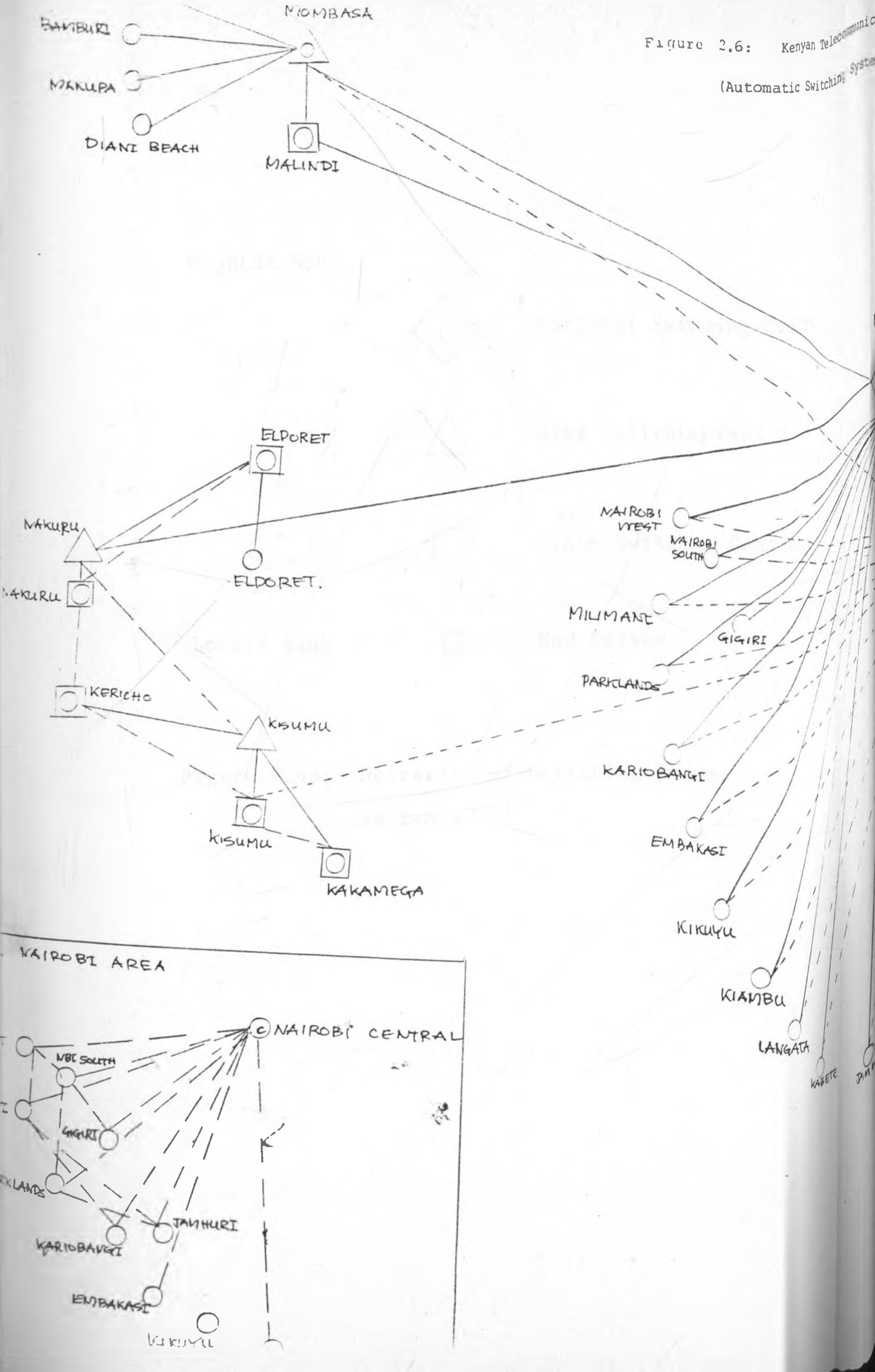

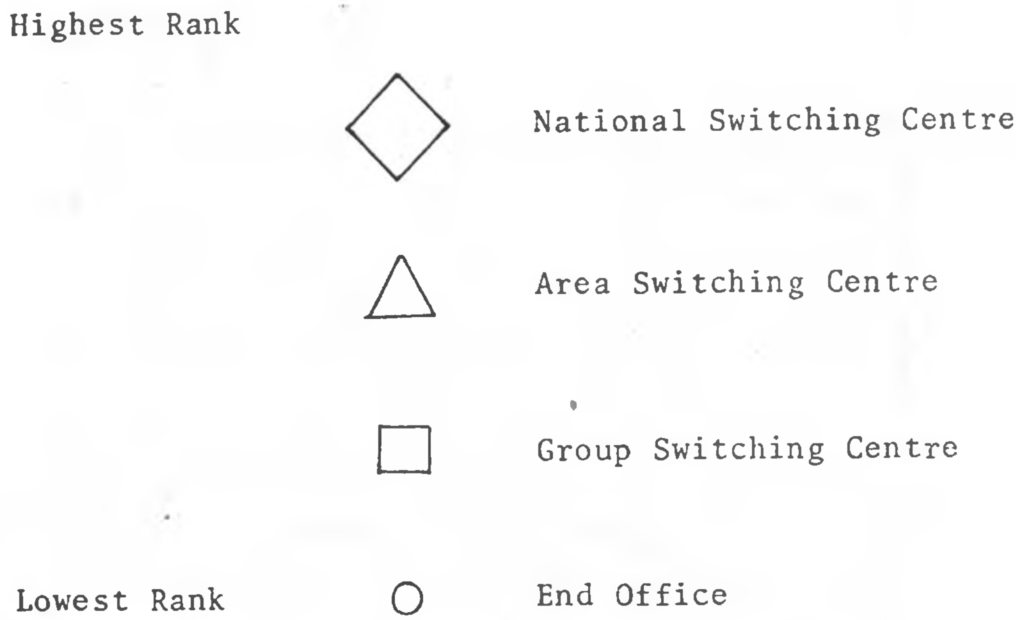

Figure 2.6a: Heirarchy of Switching Systems in Kenya

CHAPTER THREE

TELECOMMUNICATIONS TRAFFIC IN KENYA - MEASUREMENTS

In chapter 2 the telecommunications network was reviewed with a view to introducing the various services that are offered by it. To provide a communications service of this nature at a reasonable cost the network should necessarily be designed such that it satisfies the communications needs of the users; but does so with just the amount of switching equipment and transmission plant necessary to meet a specified standard of service. In order to accomplish this the network designers must have access to certain vital information.

In a general planning and installation cycle of a telecommunications network there are seven basic activities which are undertaken as Fig. 3.1 illustrates.

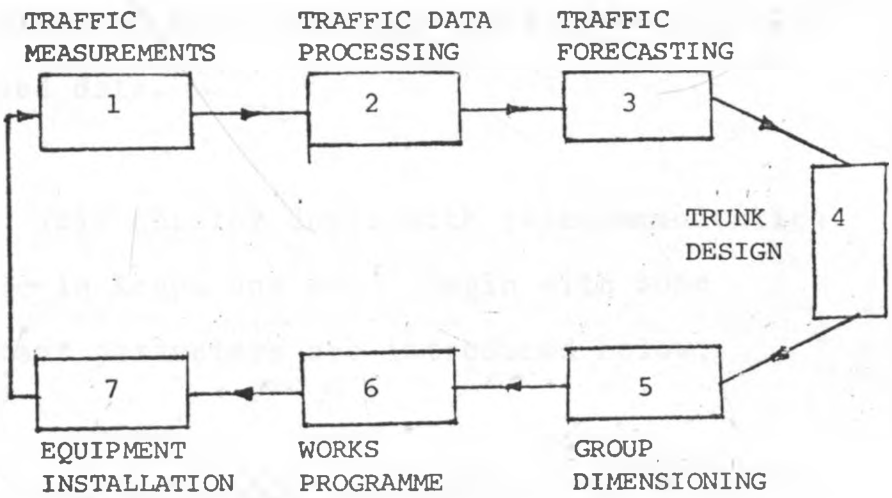

Fig. 3.1: Typical Planning and installation cycle of a Telecommunications network.

As can be appreciated five out of the seven activities involve traffic engineering. Before the network designer can effectively accomplish his objective of evolving an efficient network he must know the traffic intensities offered by each group of subscribers to every other group. He must have some idea of the characteristics of the traffic flows and the effect of splitting or merging them from point to point in the network. This information is obtained by means of collection and analysis of traffic data. This data is then used to forecast future traffic growth and forms the basis for network dimensioning. Any network congestion is monitored from this collected and analysed data.

This chapter deals with telecommunication traffic in Kenya and to begin with some important parameters are introduced below:

Telecommunications Traffic refers to the aggregate of communication messages carried between two or more points in a telecommunications network.

The traffic intensity on a group of circuits or devices is dependent on the total number of messages in progress simultaneously. The unit of traffic is the 'erlang' which is dimensionless. One erlang of traffic represents one occupied circuit carrying a telecommunications message. To put it another way one erlang of traffic intensity on one traffic circuit represents continuous occupancy of that circuit. When considering a group of circuits therefore, the traffic intensity in erlangs is the number of "call seconds per second" or the number of "call hours per hour".

For planning and dimensioning purposes it is more meaningful to consider the average rather than instantaneous traffic intensity, with the average being computed over 60 minutes.

The Volume of Traffic is often times refered to and has units of erlang hours. It is dependent on the number of messages and their duration.

Thus

$$V = \int_{0}^{t} I(t)dt$$ .. where I(t) is Traffic intensity at time t. 3.1

The Holding Time is the duration of the message and consequently the time of occupation of the transmission circuit and switching equipment.

Call arrivals as is suggested gives an idea of the times at which telecommunications messages arrive at a stage in the network.

Consider now traffic flow with the following characteristics,

(i) holding times t_1 t_2 ...... t_n; n = number of calls

(ii) duration period under consideration = T

The traffic intensity in erlangs is given by

$$A = \frac{t_1+t_2+t_3 + \ldots t_n}{T} = \frac{\sum_{i=1}^{n} t_i}{T} \quad \text{------ (3.2)}$$

The average duration of the messages is given by

$$h = \frac{t_1+t_2 + \ldots t_n}{n} = \frac{\sum_{i=1}^{n} t_i}{n} \quad \text{---- (3.3)}$$

When equations 3.2 and 3.3 are combined we get

$$A = \frac{\sum_{i=1}^{n} t_i}{T} = \frac{nh}{T} \text{ erlangs} \quad \text{--- (3.4a)}$$

$$= \frac{n}{T/h} \quad (3.4b)$$

In otherwords the average traffic intensity is equal to the number of messages arriving during the average holding time.

Congestion can best be defined by considering a circuit group to which the traffic offered is denoted A_o. If this circuit group is not large enough some of the offered traffic is not carried but is blocked instead. Let A_c denote the carried traffic; in the present situation

$$A_c < A_o$$

The ratio between blocked traffic and carried traffic is reffered to as congestion

$$B = \frac{A_o - A_c}{A_o} \quad \text{---------} \quad (3.5a)$$

and

$$A_c = A_o(1-B) \text{ erlangs} \quad \text{-----} \quad (3.5b)$$

Having introduced the fundamentals of traffic engineering we now look at three activities of traffic engineering in detail in this and subsequent chapters.

These activities are traffic measurements, traffic data processing and growth forecasting.

3.1 TRAFFIC MEASUREMENTS

As has been stated previously traffic in a network is observed for two major reasons. Firstly it provides measurements of data to give information about the traffic being handled at each point in the network. This facilitates easy monitoring of congestion or any unusual behaviour of systems in the network. Thus secondly it provides information on the necessary supervision of the network so that the required grade of service can be maintained at all times.

The measurements that are most frequently taken are traffic intensity measurements, traffic dispersion measurements, holding time measurements and grade of service measurements.

For the purposes of this project traffic intensity measurements were taken, and those are discussed in more detail below.

3.1.1 Traffic Intensity Measurements

Traffic intensity measurements are required for the long term planning of the network as well as for the day-to-day management of the same. These measurements are used to give indications as to when an existing switching point may need to be extended, and also to assist in the specifications for new exchanges.

Telecommunications traffic is generated by calls or messages arriving in a system (of the network), staying connected for a certain duration (holding time) before disconnection. Thus theoretically it is possible to obtain traffic intensity measurements by simply observing the arrival of each message and its duration. In other words if a group of circuits is scanned to determine the instantaneous circuit occupancy, data can be obtained from which the carried traffic intensity can be deduced. In practice this data is obtained in one of the following ways:

(i) Scanning periodically and recording the number of occupied circuits in the group.

(ii) Continuously recording the number of occupied circuits of the group.

(iii) Continuously recording and integrating the number of occupied circuits of the group.

In this project the first method of scanning periodically was adopted, with the result of each scan being the number of occupied circuits X(t) at scan time t_i. In chapter 2 it was stated that the bulk of the automatic switching systems in Kenya (at the time when this work was being undertaken) was made up of crossbar exchanges. Further, a look at Fig. 2.6 illustrates the fact that most Group Switching Centres (GSC's) are of crossbar types, and for this reason the method used for measuring traffic intensities in crossbar exchanges will be described in detail. As far as possible throughout the traffic measurement exercise, measurements were done at the crossbar exchange end. Thus considering two exchanges A and B for example (Fig. 3.2).

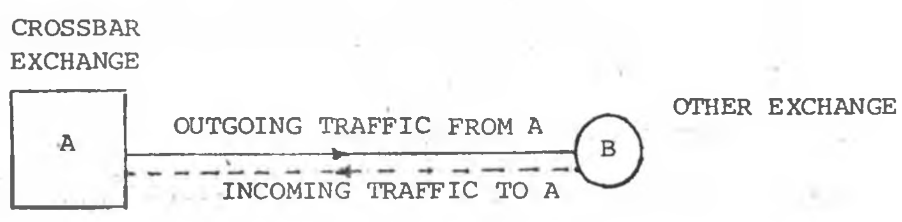

Figure 3.2: Connection of two exchanges A and B

The traffic intensities on both the outgoing route from A and the incoming route from B are measured at A which is a crossbar exchange.

3.1.2 Traffic Intensity Measurements in Crossbar Exchange

Crossbar exchanges are common controlled switching systems offering full availability. In the Kenyan network in so far as traffic intensity measurements are concerned the exchanges are grouped into two groups, one group to which the traffic measuring equipment is provided and the other where none is provided.

In Fig. 3.3 is illustrated a typical incoming circuit to a crossbar exchange. The circuit is considerably simplified to show only the relevant parts for our purposes.

The arrangement of Fig. 3.3 shows an exchange X as the originating exchange. The message may be originated by a subscriber on exchange X; or if X has transit facilities the message may be originated from another preceding switch. Y is the receiving exchange,

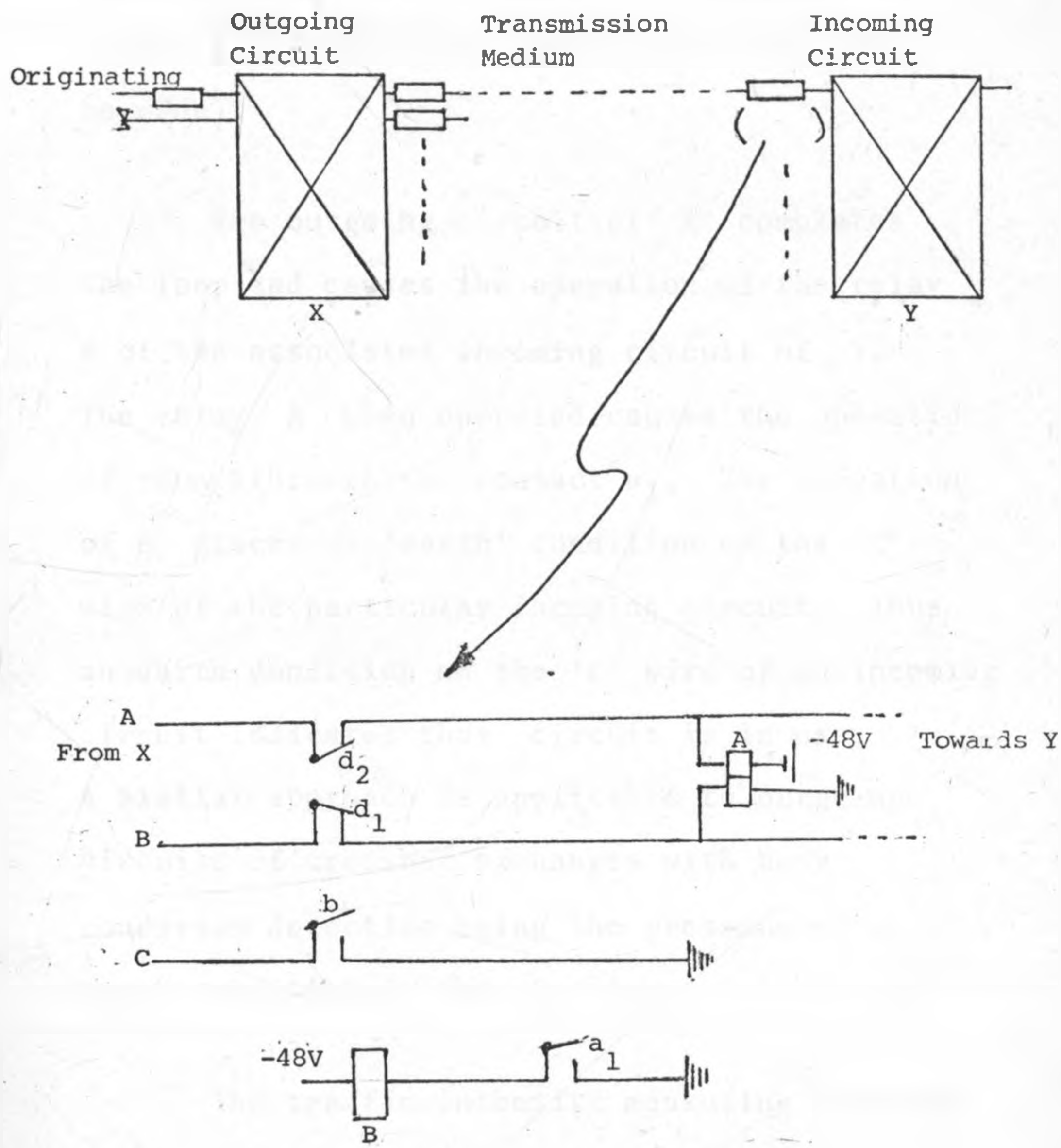

Figure 3.3:- Simplified incoming circuits of a crossbar exchange

accommodating the subscriber required for communication (This is only one example of the kinds of communication connections that can be made).

The outgoing circuit of X. completes the loop and causes the operation of the relay A of the associated incoming circuit of Y. The relay A when operated causes the operation of relay B through the contact a_1, The operation of B places an 'earth' condition on the 'C' wire of the particular incoming circuit. Thus an earth condition on the 'C' wire of an incoming circuit indicates that circuit is in use. A similar approach is applicable to outgoing circuits of crossbar exchanges with busy condition detection being the presence of an earth condition on the C wire.

The traffic intensity measuring equipment in the crossbar exchange adopts the above principle to detect busy conditions on circuits. Its operation is outlined briefly below.

3.1.3 Traffic Measuring Equipment

This equipment adopts a simultaneous operation measuring method, where the number of busy circuits is counted at predetermined intervals and recorded on a counter.

Figure 3:4 illustrates the trunking diagram to show how the equipment is connected to the other parts of the exchange.

Figure 3:5 is a diagram illustrating the various components of the equipment and will help to give clarity when outlining the operation.

Operation

The control (C) wires (previously mentioned) of all circuits for which traffic is to be measured are led in units of 21 into the SCAN circuit through rotary switches RS1 to RS5. Each rotary switch has facilities to connect 5 circuits except for the fifth switch which connects only one circuit. (The rest of the switch is used for control leads for the equipment). The rotary switches step simultaneously to bring into the scan circuit different groups of (21) circuits each time.

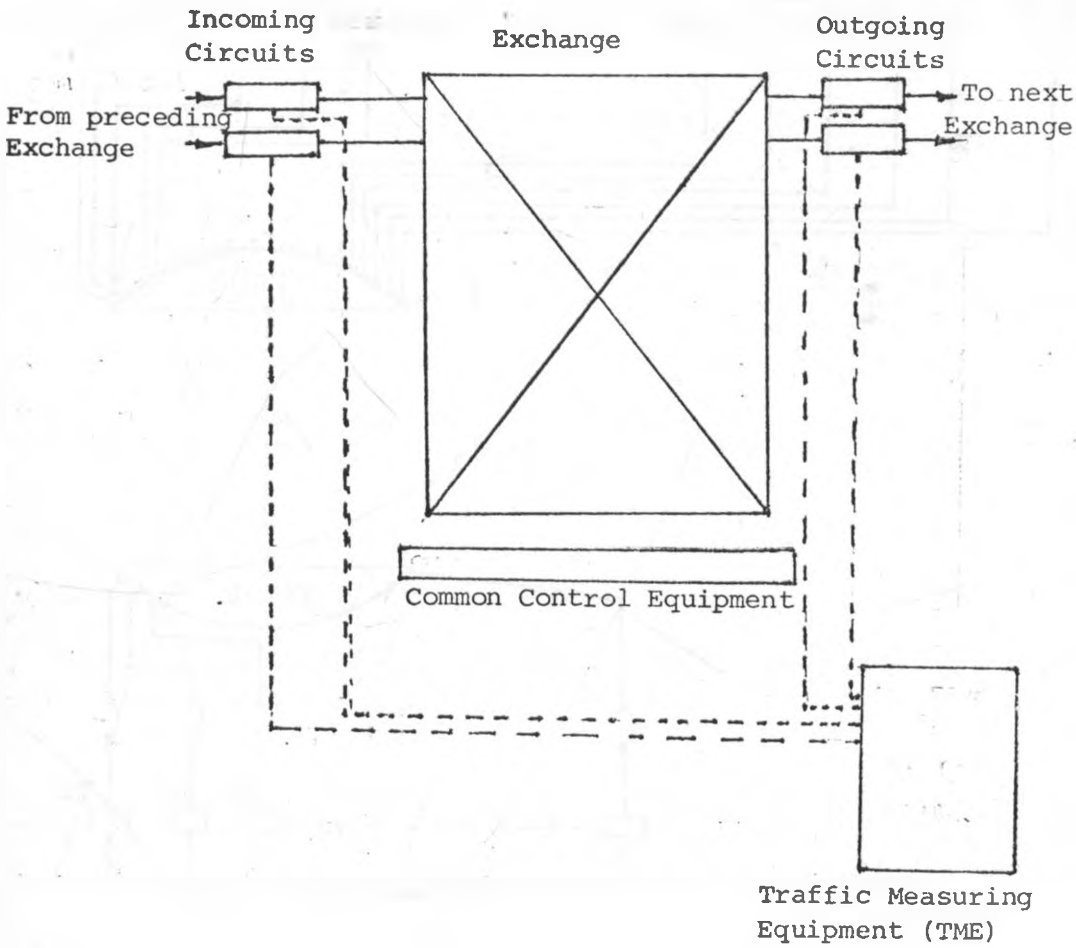

Figure 3.4: Trunking Diagram for the TME

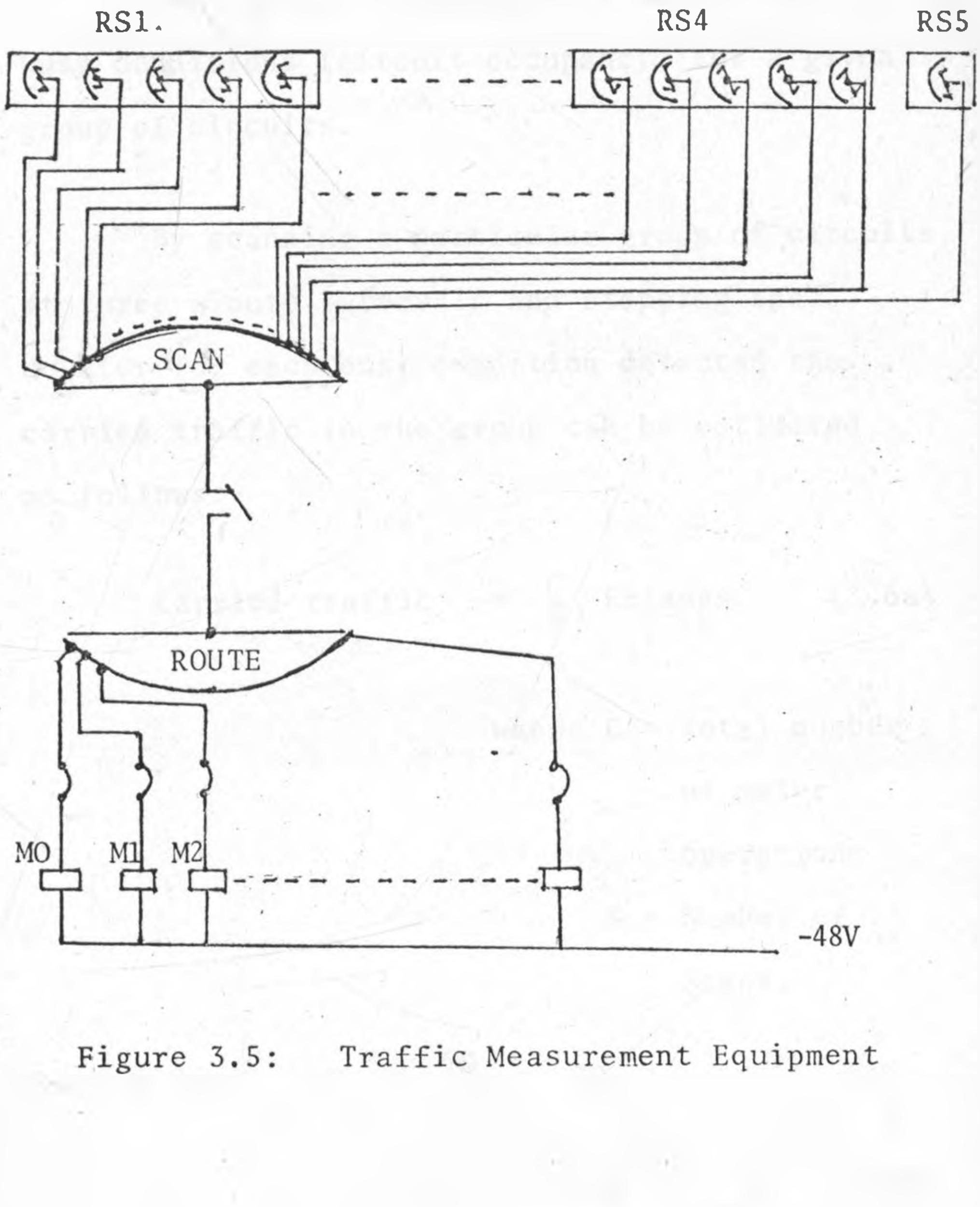

Figure 3.5: Traffic Measurement Equipment

The scan rotary switch scans the 21 circuits connected to it by the connector rotary switches (RS1 - RS5) every three minutes. A busy condition on a circuit (an earth condition on the C wire) causes an operation of the counter.

Each meter is dedicated to count the busy conditions (circuit occupancy) for a given group of circuits.

By scanning a particular group of circuits at three minute intervals and stepping the counter for each busy condition detected the carried traffic in the group can be estimated as follows:-

$$\text{Carried traffic} = \frac{C}{N} \text{ Erlangs} \qquad (3.6a)$$

where C = Total number of meter operations

N = Number of Scans.

For one hour $N = \frac{60}{3} = 20$

$$A_c = \frac{C}{20} \text{ erlangs} \qquad (3.6b)$$

For crossbar exchanges without traffic measuring equipment the carried traffic is estimated from data obtained by manual count.

By observing the 'A' relays (refer to Fig. 3:3) of the circuits in the group, busy circuits are easily identified. The scan is done at intervals of 3 minutes and thus by the same argument

$$A_c = \frac{C}{20} \text{ Erlangs.}$$

where C = <u>total number of busy counts</u>

3.1.4. Traffic Intensity Measurements in Manually operated Exchanges

The heirarchical network arrangement adopted for the Kenyan network makes it necessary in some situations for traffic measurements to be carried out in manual exchanges. Consider once more the network arrangement.

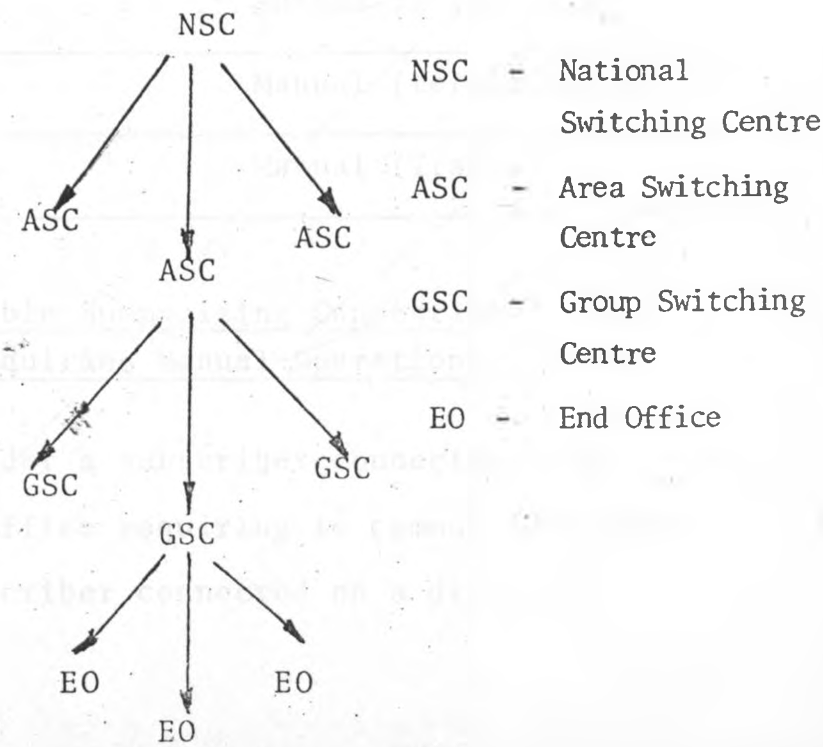

Figure 3.6: Heirarchical Network Arrangement

The NSC and ASC's are all automatic exchanges; and switch traffic to and from the GSC's. At the GSC level the switching can be done automatically or manually as is also the case at the E.O level. With this arrangement therefore there are some users who can only be connected to other users through manually operated switches. The table in Fig. 3.7 gives a summary of these connections.

From A (Originating Exchange)	To B (Terminating Exchange)
1. Manual	Manual (Terminating)
2. Manual	Manual (Transit)
3. Manual	Automatic (Terminating)
4. Manual	Automatic (Transit)
5. Automatic	Manual (terminating)
6. Automatic	Manual (Transit)

Fig. 3.7 Table Summarizing Connections Requiring Manual Operations

Consider a subscriber connected to a manual end office requiring to communicate with another subscriber connected on a different manual end office with a direct link. To connect the two communicators the operator at exchange A must call the operator at exchange B and thus the two together connect the two subscribers. The link between A and B as previously stated may either be unidirectional or bidirectional.

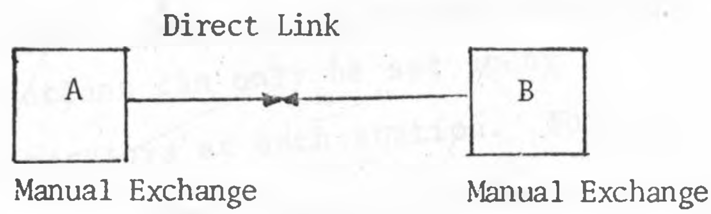

Fig. 3.7a Manual to manual Exchange Connection

(i) The second (and fourth) connections in Figure 3.7 involve calls from a manual switch requiring subscribers in other manual switches which are connected to different GSC's. The GSC's may either be automatic or manual and no direct links exist between the end offices for which communication is required.

As an example consider the arrangement in Fig. 3.7b.

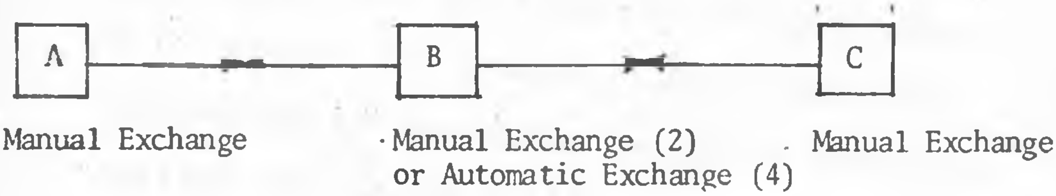

Figure 3.7b: Manual - Auto - Manual Exchange Connection

These connections can only be set up by involving operators at each station. For this reason, there are manual boards even at automatic switching centres and they serve as the only facility for connecting subscribers connected on manual exchanges.

(ii) Cases 5 and 6 involve automatic exchanges requiring to communicate with subscribers on manual exchange areas. Once again this is only possible by manual switching at both ends of the communicating links and necessitates the provision of manual operation facilities even in automatic switching centres.

Thus traffic measurements in manual exchanges play an important role in assessing teletraffic characteristics of the whole network.

The method adopted for these measurements is the subject of this sub-section:-

In manual exchanges traffic intensity measurements are taken by way of manual count. Busy circuits are counted at intervals of 3 minutes and by the same principle as considered earlier the carried traffic is given by the equation 3.6.

which is repeated here

$$A_c = \frac{C}{N} \text{ Erlangs} \qquad 3.6a$$

Figure 3.8a and 3.8b illustrate typical trunk circuits for manually operating exchanges under consideration. The circuit in 3.8a consists of four wires, the speech wires A and B and the signalling wires S and R. When an operator (at the preceeding exchange) wishes to use a circuit of this type to communicate a condition (in this case an 'earth' potential) is applied on the R (Receive wire) of the circuit. This request for communication is made visual by the lighting of lamp L1. Reference to Fig. 3.8a will reveal that the Relay 'A' of the circuit operates whenever a positive earth potential

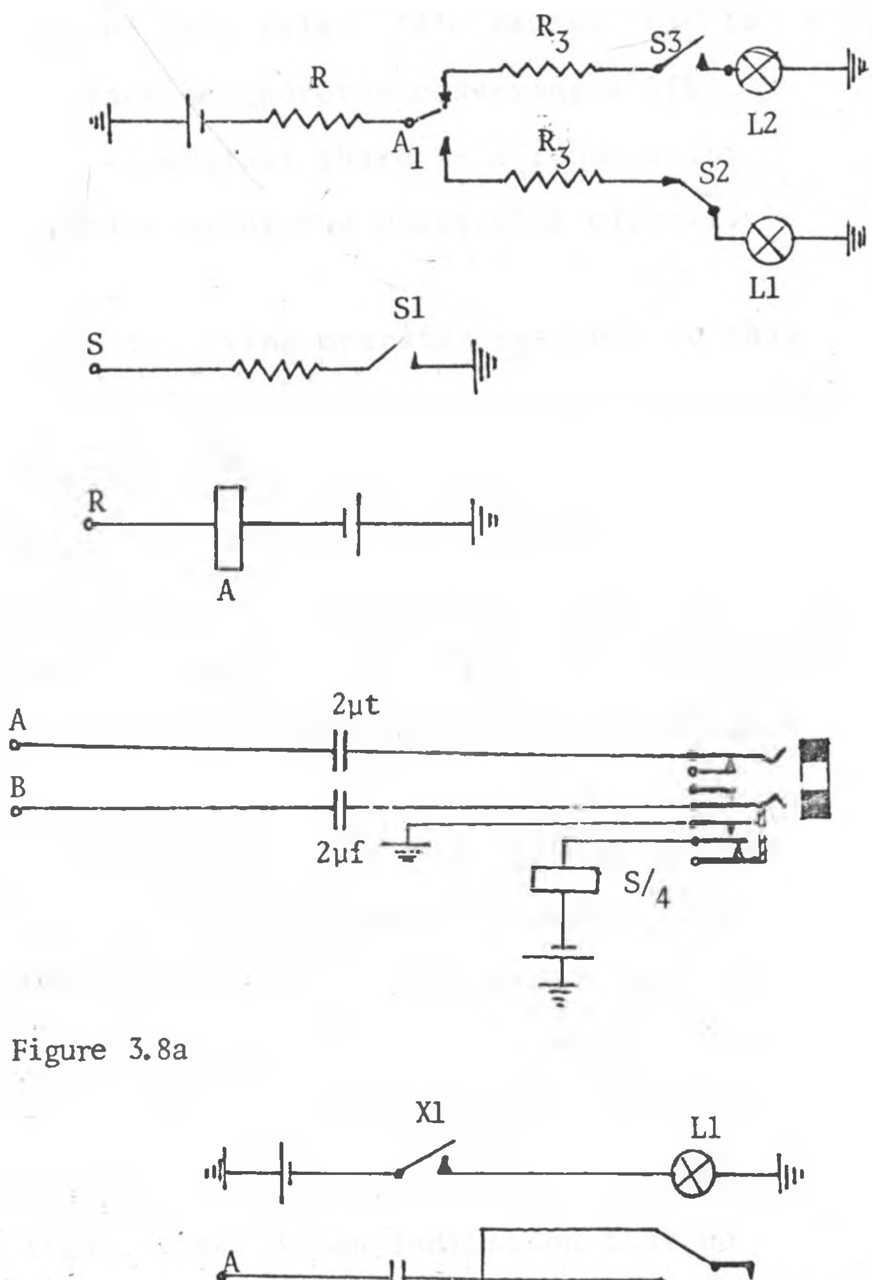

Figure 3.8a

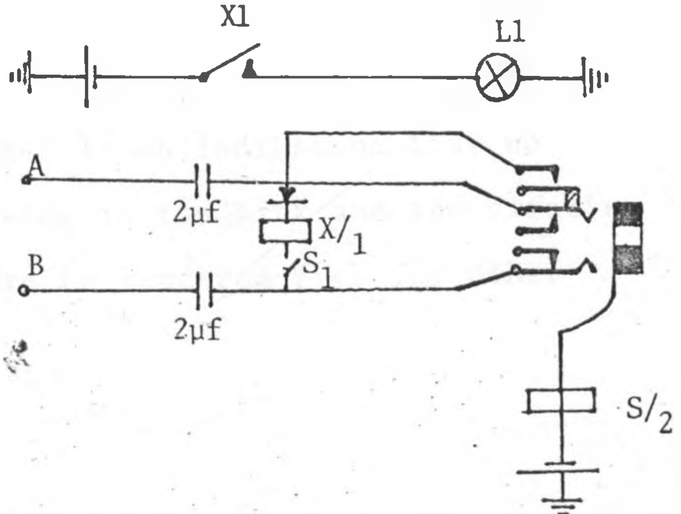

Figure 3.8b

Figure 3.8: Typical Trunk Circuits for Manual Exchanges

is applied to the R lead. Further the operation of this relay 'A' causes L1 to light. Hence an operator observing a lit lamp L1 knows that there is a request for communication using the particular circuit.

The receiving operator responds to this request by jacking into the circuit. Once again referring to the Fig. 3.8, it is noted that by jacking into the circuit the relay 'S' is caused to operate. This causes Lamp L1 to disconnect through contact S2 thus indicating that the incoming request has been attended.

On completion of the communication the calling (preceeding) operator withdraws the condition on the R wire and relay A releases. In the event where this is done while 'S' is still operated (in other words the receiving operator still holds the circuit) the lamp L2 will light. This is an indication that no traffic is flowing in the link and the circuits should therefore be rendered free for other users.

Having outlined the operation of the typical circuit the precautions that must be taken when observing traffic on manual exchanges can now be appreciated. The occupied circuits in a group are identified as those whose jacks hold answering cords. However any circuit with a cord but with L2 lit is not considered as occupied and care must be taken to distinguish it as such.

A similar argument can be followed for the circuit of Fig. 3.8b; and is not done here as it is almost identical to the preceeding discussion.

3.2 PRACTICAL MEASUREMENTS AND RESULTS

In section 3.1 the principles of traffic intensity measurements were presented. This section presents an outline of the practical procedures that were followed in making these measurements. The results are also presented.

A vital requirement for obtaining meaningful results from traffic observations is the determination of the Busy hour. Traffic is very random in nature. However there are certain consistencies that are observed over long periods of time. For example more traffic flows are observed on Mondays and Fridays and a relatively lower volume on Wednesday. In the normal work-day there is a certain consistency in the hourly variation of traffic flow. Looking across the typical work-day it is observed that a 1-hour period shows greater traffic loading on the device than any other. This 1-hour period is termed the busy-hour.

All traffic measurements must be carried out during the busy hour and busy-hour traffic forecasts are based on this. Any condition which can be withstood by a device during the busy-hour will be comfortably accomodated during any other time. Hence if the required Grade of service is achieved in a system based on the busy-hour traffic, the efficient operation of the system is guaranteed at all other times. In Kenya the busy hour is observed to be during the period 9.30 a.m to 10.30 a.m. for most exchanges. It differs somewhat in exchanges with a majority of residential subscribers, in which case the traffic peaks in the early evening hours.

For the purposes of this project all measurements were taken simultaneously during the hour 9.30 a.m. - 10.30 a.m; and it is assumed that the effect of the difference in busy hour for residential areas will not significantly corrupt the analysis.

3.2.1 Observation of Traffic Data.

The traffic intensity measurement exercise involves several steps and the procedure followed is best presented by considering an example.

Let us consider an exchange 'PROJECT' at which measurements are to be made. Let this exchange be connected to 5 other exchanges by uni-directional links as illustrated in Fig. 3.9.

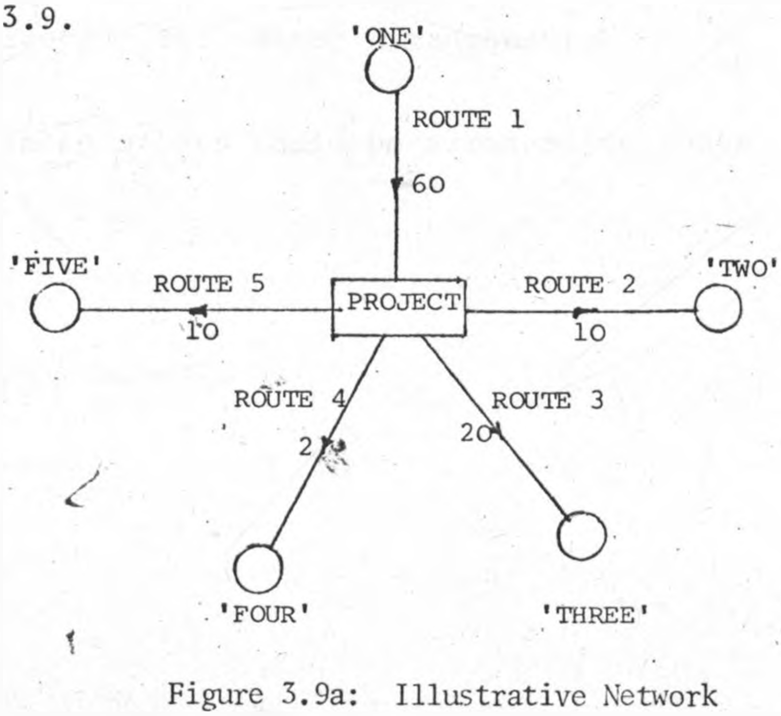

Figure 3.9a: Illustrative Network

The number of circuits in each link (route) is indicated on the figure, as well as the direction of traffic flow. Hence traffic flows from exchange ONE to PROJECT; whereas traffic flows from PROJECT to all the other four exchanges.

In section 3.1.2 it was stated that there are meters dedicated to count circuit occupancies for each route. Thus in the exchange PROJECT, there would be five meters each dedicated for the observation of traffic for one of the five routes.

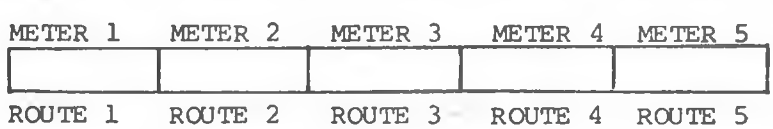

Figure 3.9b: Meter Arrangements

These meters could be arranged as above.

	METER 1	METER 2	METER 3	METER 4	METER 5
DAY 5	05000	30473	19860	04550	25200
DAY 4	04050	30380	19600	04522	25100
DAY 3	03190	30284	19250	04500	24900
DAY 2	02240	30190	18930	04480	24000
DAY 1	01390	30100	18600	04450	23900
INITIAL	00450	30011	18342	04425	23845
	ROUTE 1	ROUTE 2	ROUTE 3	ROUTE 4	ROUTE 5

Fig. 3.9c Example of filled table

Step 1

The initial readings of the meters are recorded before the beginning of the busy hour on the first day of measurements. The traffic measuring equipment (see 3.1.3) is started at the beginning of the busy hour and stopped at the end of the busy hour. The meter readings are again recorded on the row written DAY 1.

Step 2 .

The traffic measuring equipment is started at the beginning of the busy hour and stopped at the end of the hour. The meter readings are recorded on the appropriate row (DAY 2).

This is repeated for five consecutive working days so that an average can be obtained to eliminate extreme erroneous readings.

Fig. 3.9c illustrates a completely filled out table with all meter readings for 5 days entered. For exchanges where no measuring equipment is available the busy circuits are simply counted and recorded).

Step 3.

By subtracting the initial meter readings from those taken on the first day the simultaneous meter operations for the first day are determined. Similarly the circuit occupancy counts for the second day are obtained by subtracting the readings of DAY 1 from those of DAY 2. The same is done for days 3,4 and 5. Refering to equation 3.6; at this point in the measurement exercise the value of C has been determined for each route for each of the five days.

For our example these values are shown in Fig. 3.9d.

	ROUTE 1	ROUTE 2	ROUTE 3	ROUTE 4	ROUTE 5
DAY 5	950	93	260	28	100
DAY 4	860	96	350	22	200
DAY 3	950	94	320	20	900
DAY 2	850	90	330	30	100
DAY 1	940	89	258	25	145

Fig. 3.9d Values of 'C' (simultaneous meter operations)

Step 4.

Recall that for 60 minutes

$$A_c = \frac{C}{20} \quad \text{Erlangs} \qquad 3.6a$$

Thus by dividing the values in 3.9d by 20 the carried traffic in each route is obtained in Erlangs. Fig. 3.9e gives the carried traffic in the various routes of our example.

Figure 3.9e: Carried Traffic

DAY 5	47.5	4.7	13.0	1.4	5.0
DAY 4	43.0	4.8	17.5	1.1	10.0
DAY 3	47.5	4.5	16.0	1.0	45.0*
DAY 2	42.5	4.5	16.5	1.5	5.0
DAY 1	47.0	4.7	12.9	1.8	7.3
AVERAGE	45.5	4.7	15.2	1.4	6.9

* - This entry is disregarded as it obviously represents abnormal operation of some equipment.

The above procedure was followed for all switching centres in the network in cooperation with the personnel charged with the responsibility of maintaining the exchanges. Each person availed the traffic data observed through existing established procedures within the Kenya Posts and Telecommunications Corp which involved mailing the data to a central point from where it was collectively available. The measurements were done over the weeks of October to December of 1983 and the averages taken in each case.

3.2.2 Results

The results of the measurements are presented in the tables of Fig. 3.10, where the average carried traffic intensity between automatic exchanges during the busy hour is given. The representation is in matrix form, with the originating (calling) exchanges listed on the left hand side of the matrix and the terminating (called) exchanges arranged as the columns of the matrix. This arrangement gives an nxn matrix for a network with n switching systems. The entries in the matrix are each made up of two figures. The first figure gives the number of circuits making up the route, whereas the second figure gives the carried traffic in erlangs.

As an example consider the matrix of Figure 3:10(b) with five exchanges, giving a 5x5 matrix. The interpretation is as follows. The route from Nairobi (NSC) to Kisumu is made up of 65 circuits and they carried 37.5 erlangs. Similarly for example the own-exchange traffic in Kericho is 12.9 erlangs, but 48 circuits can be used to carry this traffic.

The entries marked HU are those routes used as High Usage routes. This type of route is a first priority route for traffic and any excess traffic offered to this route overflows to an alternative route. This type of route can never be said to have congestion.

Fig. 3:10(a) - COAST NETWORK

EXCHANGE	NAIROBI(NSC)	MOMBASA(GSC)	MALINDI	BAMBURI	D. BEACH	CHANGAMWE	MAKUPA	NYALI
NAIROBI (NSC)		140/79.3	11/4.8					
MOMBASA(GSC)	150/101.6	126/82.2	29/7.0	24/22.1	17/8.9	55/47.7	74/39.2	54/30.2
MALINDI	18/3.8	29/7.4	54/12.1					
BAMBURI		20/17.5		25/2.7				
D. BEACH		18/9.5			6/2.1			
CHANGAMWE		55/28.6				30/6.1		
MAKUPA		70/27.9					25/2.0	
NYALI		73/38.8						18/4.7

KEY

x/y - Route Consists of X circuits carrying y Erlangs.

Fig. 3:10(b) - KISUMU NETWORK

EXCHANGE	NAIROBI(NSC)	KISUMU(ASC)	KISUMU(GSC)	KAKAMEGA	KERICHO	NAKURU(ASC)	NAKURU(GSC)
NAIROBI(NSC)		65/37.5	30/28.3^{HU}	7/2.6 ^{HU}		56/21.6	32/28.0
KISUMU(ASC)	66/31.5		48/30.9	16/9.4	17/12.3	14/2.0	
KISUMU(GSC)	30/26.3	48/32.2	132/30.9	5/3.6			8/5.1^{HU}
KAKAMEGA	5/2.2	15/11.0	5/2.1^{HU}	36/10.5			
KERICHO	12/9.8^{HU}	11/7.0			48/12.9		4/2.8^{HU}
NAKURU ASC	54/35.2	14/4.6					54/16.6
NAKURU GSC	32/28.5		8/4.8		4/2.4	54/35.5	108/40.7

KEY

HU = High Usage Route

x/y - Route consists of X circuits carrying y erlangs.

Fig. 3:10(c) - NYERI NETWORK

EXCHANGE	NAIROBI(NSC)	NYERI(ASC)	NYERI(GSC)	EMBU GSC	MERU(GSC)	KARATINA	NANYUKI
NAIROBI(GSC)		10/3.6	$55/18.5^{HU}$	$10/8.5^{HU}$	$26/7.6^{HU}$		$13/9.8^{HU}$
NYERI(ASC)	22/9.1		45/3.8	10/6.3	18/3.7		5/1.4
NYERI(GSC)	68/34.0	45/3.6	68/35.8	4/2.3		23/7.9	4/2.1
EMBU(GSC)	12/8.4	10/8.7	5/2.3	36/11.3			
MERU(GSC)	29/9.9	19/7.9			54/18.3		
KARATINA			24/9.8			30/4.4	
NANYUKI	18/12.6	6/1.3	4/2.7				18/16.4

KEY

HU = High Usage Route

x/y - Route consists of X circuits carrying y erlangs.

Fig. 3.10(d) - NAKURU NETWORK

EXCHANGE	NAIROBI(NSC)	NAKURU(ASC)	NAKURU(GSC)	ELDORET
NAIROBI(NSC)		56/21.6	32/28.0^{HU}	18/11.7^{HU}
NAKURU(ASC)	54/35.2^{HU}		54/16.6	29/14.3
NAKURU(GSC)	32/28.5	54/35.5	108/40.7	7/4.4
ELDORET	31/24.2^{HU}	29/13.3	7/4.7	46/10.0

KEY

HU = High Usage Route

x/y = Route consists of x circuits carrying y erlangs.

FIGURE 3.10e: NAIROBI NETW

EXCHANGE	NAIROBI NSC	NAIROBI CENT.	NAIROBI LTDM	EMBAKASI	EASTLEIGH	KAR
NAIROBI NSC	-	100/79.0	61/34.0	17/2.2	-	14/
NAIROBI CENT.	100/95.2	427/24.15	133/69.2	17/14.6	-	40/
NAIROBI LTDM	-	100/65.2	-	43/17.9	17/10.9	69/
EMBAKASI	18/3.7	19/1.0	33/11.7	18/2.7		
EASTLEIGH	15/3.2		20/17.9		10/2.6	
KARIOBANGI	14/5.3	21/19.3[HU]	49/39.0			30/
PARKLANDS	19/10.6	20/18.7[HU]	70/49.9			
MILIMANI	40/17.5	50/43.5[HU]	70/30.4			10/
NAIROBI WEST	26/3.0	18/6.2	51/16.0			
JAMHURI PARK	20/9.7	34/23.8[HU]	45/32.5			
NAIROBI SOUTH	27/16.8	32/28.0[HU]	45/21.5			
LANGATA	10/6.0		32/23.3			
UTHIRU	3/0.5	9/1.8	16/8.9			
KIKUYU			15/9.1			
KABETE		10/1.9	28/22.9			
GIGIRI	10/1.7	10/5.2[HU]	29/14.8			

CHAPTER FOUR

GRADE OF SERVICE ON TELECOMMUNICATIONS LINKS

So far traffic data giving the traffic flowing in various links in the busy hour has been obtained. This data will next be used to assess the network as it exists and evaluate to what extent it meets its objectives. One of these objecti ves is to provide an acceptable grade of service to the users on the network.

The grade of service can be expressed as a blocking probability or a percentage of calls permitted to fail.

In Chapter 3 call congestion was defined as

$$B = \frac{\text{Blocked Calls}}{\text{Offered Calls}}$$

$$= \frac{A_o - A_c}{A_o} \qquad 3.5a$$

Now another parameter, time congestion E is defined as

$$E = \frac{\text{Time during which all circuits are occupied}}{\text{Duration of measurements.}}$$

In full availability systems where calls arrive at random B = E. With limited availability and/or other call arrival distributions $E \neq B$, the difference being small enough to be ignored in some cases.

A number of factors are considered when deciding on the numerical values for the grades of service at various points in a telecommunications network. Some of these factors are customer requirements and expectations, equipment costs, loss of revenue due to blocked traffic, unforseen traffic loads and safety margins necessary to cover errors in traffic estimates. The actual grades of service chosen represent a compromise of all these requirements.

In practice the grade of service offered to users may be worse than that which was designed due to technical faults, dimensioning errors or unimplemented installation projects among other reasons.

In Kenya the designed grades of service between switching systems are given in the Figure 4.1 below.

From (Exchange)	To (Exchange)	GOS
Automatic	Automatic	0.01
Automatic	Manual	0.03
Manual	Automatic	0.1
Own-exchange		0.02

Fig. 4.1 Designed Grades of Service (Obtained from the KP & TC traffic Department).

It is observed from the table that the best grade of service is expected between two automatic exchanges; whereas maximum blocking is expected between two manually operated switching systems.

In this chapter we seek to investigate whether the designed grades of service are met on the routes linking automatic exchanges. Automatic measurements of call congestion B would require two accumulating counters, one counter incrementing whenever a call enters a system and the other incrementing for each blocked call. The measurement of time congestion E requires a counter so connected to accumulate the time periods during which all circuits are occupied. In the systems considered the measurement facilities for the quantities E and B are not incorporated, and it was therefore necessary to estimate the congestion encountered on each group of circuits from the traffic intensity measurements of Chapter 3 . This was done using a simple computer programme developed for this purpose.

4.1 Traffic Theory Models

In order to estimate the blocking encountered on the various links the relevant model to describe the behaviour of telecommunications traffic must be determined. Some of the standard telecommunications traffic theory models are the pure chance traffic model, Erlang loss model and the Engset distribution model. Each of these models involves certain assumptions as summarized below[1].

4.1.1 Pure chance traffic

This model makes the assumptions that:-

a) there is an unlimited number of circuits available so that no call that arrives is rejected.

b) calls arrive at random with a mean arrival rate.

c) the calls holding times are exponentially distributed.

This is an idealized model and forms the basis for other model theories.

4.1.2 Erlang Loss Model

The assumptions made with this model are:-

a) calls arrive at random and rejected calls (due to all circuits being busy) do not return.

b) The probability of a call arriving at the system is independent of the state of the system.

c) the system is in statistical equilibrium.

d) The number of sources that generate calls is infinite.

e) there is full availability of the circuits in the system.

f) the holding times are exponentially distributed.

The probability that all circuits (n) are busy under those assumptions is given by

$$P(n) = \frac{A^n/n!}{\sum_{j=1}^{n} A^j/j!} = E_n(A) \qquad 4.1$$

Equation 4.1 is known as the Erlang's Loss Formula and represents the call congestion.

4.1.3 Engset Distribution Model

The Engset Distribution model considers the situation where the number of sources of traffic (subscribers) is small. In this case as the number of busy sources increases the call arrival rate decreases. The pattern of call arrivals thus significantly departs from random for situations where the sources are less than 200.

The assumptions are:

a) holding times are exponentially distributed.

b) there is full availability of circuits and all lost calls do not get repeated.

The Engset distribution model would be useful in the determination of time congestion for routes linking manually operated switching systems.

4.2 Computer Programme "ERLANG B"

In this section a simple computer programme is developed to evaluate the offered traffic (A_o) to a group of circuits of a known size (N) and over which a known (measured) traffic intensity (A_c) flows. In the development of the programme it has been assumed that pure chance traffic is offered to a full availability group of circuits and that all lost calls are cleared. It is thus assumed that when a caller encounters congestion he does not make a repeated attempt.

Whereas this assumption may not seem realistic other models have been proposed[1] which show that the effect of repeated attempts is simply to increase the average call arrival rate.

The Erlang loss Model is thus assumed.

The basic equations used to estimate the offered traffic are:-

$$A_c = A_o/(1-B) \qquad 4.2$$

$$B = \frac{A_o^n/n!}{\sum_{j=o}^{n} A_o^j/j!} \qquad 4.3$$

where A_o = offered traffic (Erlangs)

A_c = carried traffic (Erlangs)

n = number of circuits

B = congestion.

Equation 4.2 relates the offered traffic to a group of circuits to the traffic carried by the route and the congestion encountered by this traffic. Equation 4.3 is the congestion function which relates the offered traffic and the number of circuits comprising a route, to congestion under the assumptions above (Erlang Loss Model)

The procedure adopted here is to initially assume that all the offered traffic is successfully carried. The measured value for carried traffic A_c is thus substituted for the offered traffic A_o in equation 4.3.

This gives

$$B_1 = \frac{A_c^n/n!}{\sum_{j=1}^{n} A_c^j/j!} \tag{4.3a}$$

The value of congestion B_1 is then inserted into equation 4.2 to obtain

$$A_{o_1} = A_c/(1-B_1) \tag{4.2a}$$

A_{o_1} is the traffic offered when A_c erlangs is carried in a route of n circuits with congestion B_1; and is the required estimate for the offered traffic.

The value $|A_{o_1} - A_c|$ reveals whether or not a significant amount of congestion was encountered on the route.

Figure 4.2 illustrates a flowchart of the programme. It consists of one main programme (Fig. 4.2) and a subroutine (Fig. 4.2a). The subroutine calculates factorials. utilizing one loop.

The main programme calculates congestion using equation 4.3(a) with the carried traffic (A_c) and the number of circuits (n) as the known variables.

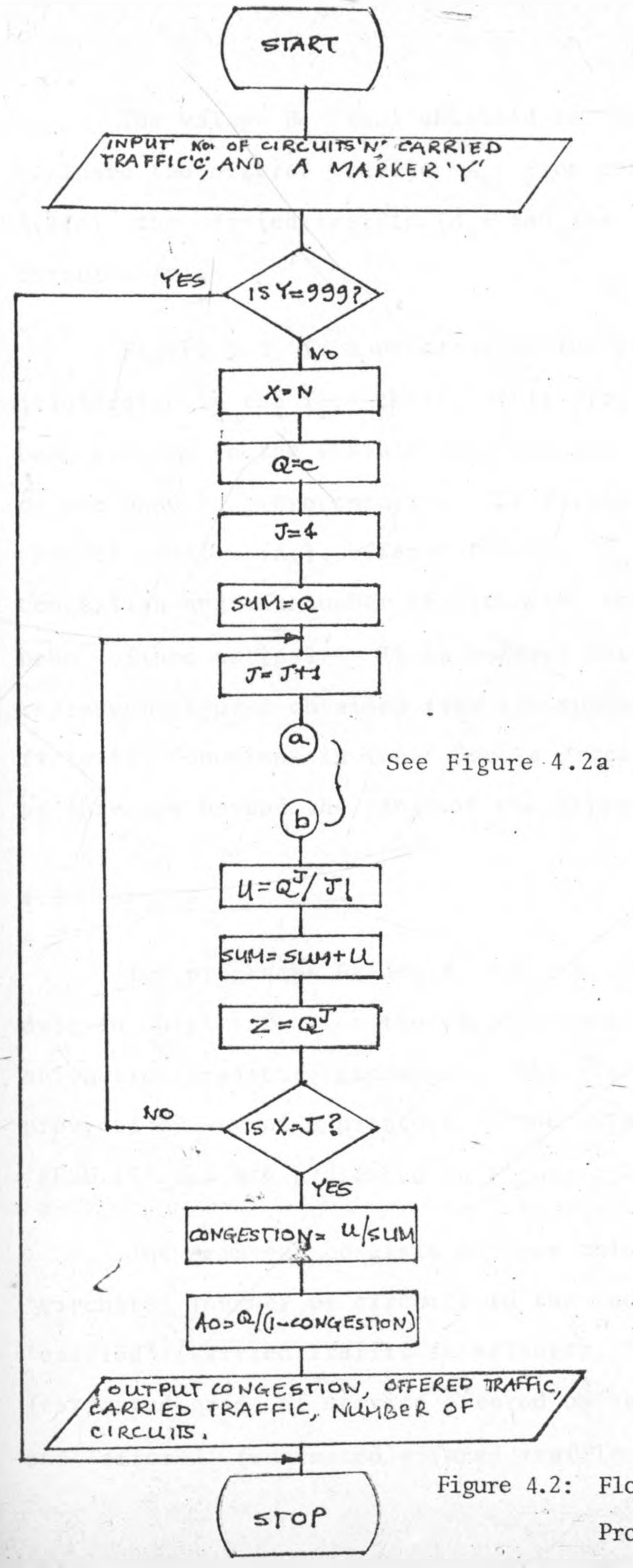

Figure 4.2: Flowchart for Programme 'ERLANG B'

The value B_1 thus obtained is then used to evaluate the offered traffic A_o from equation 4.2(a) the carried traffic (A_c) and the number of circuits (n).

Figure 4.3 is a printout of the programme illustrated in the flow chart. This programme has been written in the FORTRAN language and was developed on the WANG PC microcomputer. The figures for carried traffic (A_c), offered traffic (A_o), congestion and the number of circuits (n) have been defined as real. It is however necessary to represent figures obtained from the summation and factorial functions in their double precision forms as they are beyond the range of the microcomputer.

4.3 Results

The programme Erlang B was run using the data in Chapter 3 for the various routes linking automatic (crossbar) exchanges. The results are provided by way of a printout of the output file 'RESULTS' and are presented in Figure 4.4.

The printout consists of four columns headed 'circuits' (number of circuits in the route), 'carried' (carried traffic in erlangs), 'congestion' (estimated grade of service offered on the route) and 'offered' (estimated offered traffic in erlangs).

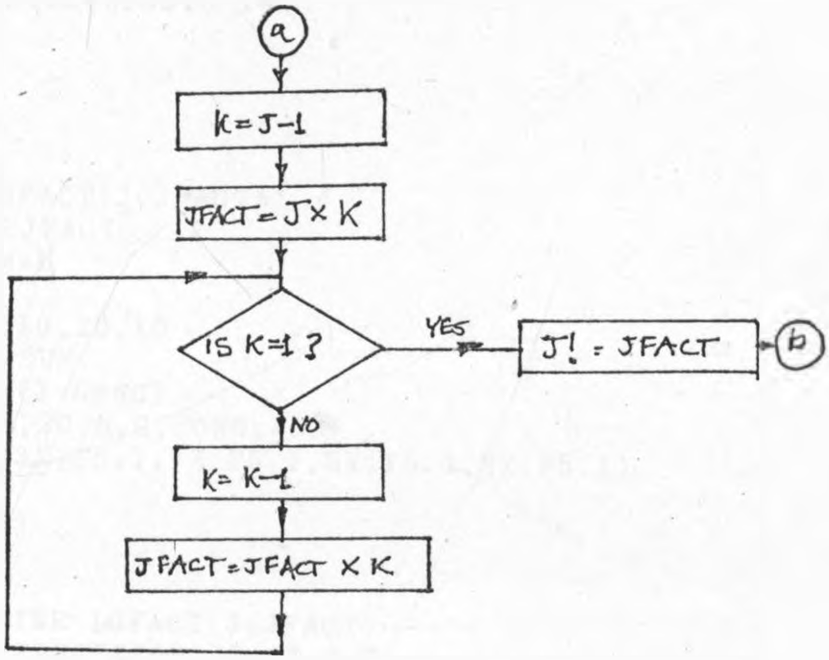

Figure 4.2a: Flowchart for Subroutine LGFACT

```
C       PROGRAM ERLANG B
        INTEGER Y
        REAL AOFF,CONG,N,C
        DOUBLE PRECISION SUM,U,JFACT,Z,Q,X,J
        OPEN(8,FILE='RESULTS',STATUS='NEW')
        WRITE(8,25)
25      FORMAT(2X,'CIRCUITS',4X,'CARRIED',4X,'CONGESTION',4X,'OFFERED
1       WRITE(*,5)
5       FORMAT(2X,'INPUT TWO NUMBERS XXX.X AND XXX.X AND INTEGER XXX'
        READ(*,15)N,C,Y
15      FORMAT(F5.1,F5.1,I3)
        IF (Y.EQ.999)GOTO 100
        X=N
        Q=C
        J=1D0
        SUM=Q
10      J=J+1
        CALL LGFACT(J,JFACT)
        U=Q**J/JFACT
        SUM=SUM+U
        Z=Q**J
        IF(X-J)10,20,10
20      CONG=U/SUM
        AOFF=Q/(1-CONG)
        WRITE(8,30)N,C,CONG,AOFF
30      FORMAT(3X,F5.1,7X,F5.1,8X,F5.4,8X,F5.1)
        GOTO 1
100     CLOSE(8)
        STOP
        END
        SUBROUTINE LGFACT(J,JFACT)
        DOUBLE PRECISION JFACT,J,K
        K=J-1
        JFACT=J*K
35      IF(K-1)40,45,40
40      K=K-1
        JFACT=JFACT*K
        GOTO 35
45      RETURN
        END
```

Figure 4.3: Programme to evaluate offered traffic A_o given carried traffic A_c, and number of circuits n.

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CIRCUITS	CARRIED	CONGESTION		OFFERED	ROUTE	
140.0	79.3	.0000	79·3	79.3	NAIROBI NSC	– MOMBASA GSC
11.0	4.8	.0065	4·8	4.8	”	– MALINDI
150.0	101.6	.0000	101·6	101.6	MOMBASA GSC	– NRB. NSC
126.0	82.2	.0000	82·2	82.2	”	– MOMBASA GSC
29.0	7.0	.0000	7·0	7.0	”	– MALINDI
24.0	22.1	.1064	27·5	24.7	”	– BAMBURI
17.0	8.9	.0053	8·9	8.9	”	– DIANI BEACH
55.0	47.7	.0363	50·7	49.5	”	– CHANGAMWE
74.0	39.2	.0000	39·2	39.2	”	– MAKUPA
54.0	30.2	.0000	30·2	30.2	”	– NYALI
18.0	3.8	.0000	3·8	3.8	MALINDI	– NRB NSC
29.0	7.4	.0000	7·4	7.4	”	– MSA GSC
54.0	12.1	.0000	12·1	12.1	”	– MALINDI
20.0	17.5	.0973	2·4	19.4	BAMBURI	– MSA GSC
25.0	2.7	.0000	2·7	2.7	”	– BAMBURI
18.0	9.5	.0047	9·5	9.5	DIANI BEACH	– MSA GSC
6.0	2.7	.0396	2·8	2.8	”	– DIANI BEA
55.0	28.6	.0000	28·6	28.6	CHANGAMWE	– MSA GSC
30.0	6.1	.0000	6·1	6.1	”	– CHANGAMWE
70.0	27.9	.0000	27·9	27.9	MAKUPA	– MSA GSC.
25.0	2.0	.0000	2·0	2.0	”	– MAKUPA
73.0	38.8	.0000	38·8	38.8	NYALI	– MSA. GSC.
18.0	4.7	.0000	4·7	4.7	”	– NYALI

Figure 4.4a: Coast Network

CIRCUITS	CARRIED	CONGESTION	OFFERED		ROUTE
56.0	21.6	.0000	21.6	21.6	NAIROBI NSC – NAKURU ASC
32.0	28.0	.0665	32.3	30.0	" – NAKURU GSC
18.0	11.7	.0225	12.0	12.0	" – ELDORET
54.0	35.2	.0007	35.2	35.2	NAKURU ASC – NRB NSC
54.0	16.6	.0000	16.6	16.6	" – NAKURU GSC
29.0	14.3	.0002	14.3	14.3	" – ELDORET
32.0	28.5	.0736	32.0	30.8	NAKURU GSC – NAIROBI NSC
54.0	35.5	.0009	35.5	35.5	" – NAKURU ASC
7.0	4.4	.0855	4.7	4.8	" – ELDORET
31.0	24.2	.0321	25.3	25.0	ELDORET – NAIROBI NSC
29.0	13.3	.0001	13.3	13.3	" – NAKURU ASC
7.0	4.7	.1031	5.6	5.2	" – NAKURU GSC
46.0	10.0	.0000	10.0	10.0	" – ELDORET

Figure 4.4b:Nakuru Network

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CIRCUITS	CARRIED	CONGESTION		OFFERED	ROUTE	
65.0	37.5	.0000	37.5	37.5	NAIROBI NSC	- KISUMU ASC
30.0	28.3	.1031	HU	31.6	,,	- KISUMU GSC
7.0	2.6	.0129	HU	2.6	,,	- KAKAMEGA
66.0	31.5	.0000	31.5	31.5	KISUMU ASC	- NAIROBI NSC
48.0	30.9	.0010	30.9	30.9	,,	- KISUMU GSC
16.0	9.4	.0149	9.5	9.5	,,	- KAKAMEGA
17.0	12.3	.0467	14.2	12.9	,,	- KERICHO
14.0	2.0	.0000	2.0	2.0	,,	- NAKURU ASC
30.0	26.3	.0711	30.0	28.3	KISUMU GSC	- NAIROBI NSC
48.0	32.2	.0020	32.3	32.3	,,	- KISUMU ASC
5.0	3.6	.1686	5.1	4.3	,,	- KAKAMEGA
8.0	5.1	.0753	HU	5.5	,,	- NAKURU GSC
5.0	2.2	.0551	2.3	2.3	KAKAMEGA	- NAIROBI NSC
15.0	11.0	.0588	2.1	11.7	,,	- KISUMU ASC
5.0	2.1	.0486	HU	2.2	,,	- KISUMU GSC
36.0	10.5	.0000	10.5	10.5	,,	- KAKAMEGA
12.0	9.8	.1121	HU	11.0	KERICHO	- NAIROBI NSC
11.0	7.0	.0478	7.5	7.4	,,	- KISUMU ASC
48.0	12.9	.0000	12.9	12.9	,,	- KERICHO
4.0	2.8	.1979	HU	3.5	,,	- NAKURU GSC
14.0	4.6	.0002	4.6	4.6	NAKURU ASC	- KISUMU ASC
54.0	16.6	.0000	16.6	16.6	,,	- NAKURU GSC
8.0	4.8	.0615	4.9	5.1	NAKURU GSC	- KISUMU GSC
4.0	2.4	.1542	2.7	2.8	,,	- KERICHO
54.0	35.5	.0009	35.5	35.5	,,	- NAKURU ASC
10.0	3.0	.0009	3.0	3.0	NAIROBI NSC	- NYERI ASC
55.0	18.5	.0000	HU	18.5	,,	- NYERI GSC
10.0	8.5	.1446	HU	9.9	,,	- EMBU
26.0	7.6	.0000	HU	7.6	,,	- MERU
13.0	9.8	.0779	HU	10.6	,,	- NANYUKI
22.0	9.1	.0001	9.1	9.1	NYERI ASC	- NAIROBI NSC
45.0	3.8	.0000	3.8	3.8	,,	- NYERI GSC
10.0	6.3	.0529	6.8	6.7	,,	- EMBU
18.0	3.7	.0000	3.7	3.7	,,	- MERU
5.0	1.4	.0147	1.4	1.4	,,	- NANYUKI

-Figure 4.4c: Kisumu Network
Nyeri Network

CIRCUITS	CARRIED	CONGESTION		OFFERED	ROUTE
100.0	79.0	.0031		79.2	NAIROBI NSC - NAIROBI CENTRAL
61.0	34.0	.0000	34.0	34.0	" - NAIROBI LTDM
17.0	2.2	.0000	2.2	2.2	" - EMBAKASI
14.0	7.0	.0071	7.1	7.1	" - KARIOBANGI
20.0	10.4	.0027	10.4	10.4	" - PARKLANDS
40.0	28.8	.0092	29.1	29.1	" - MILIMANI
27.0	5.0	.0000	5.0	5.0	" - NRB WEST
19.0	11.7	.0137	11.8	11.9	" - JAMHURI PARK
27.0	18.1	.0117	18.2	18.3	" - NAIROBI SOUTH
100.0	95.2	.0498		100.2	NAIROBI CENT - NAIROBI NSC
17.0	14.6	.1021	HU	16.3	" - EMBAKASI
40.0	22.8	.0003	HU	22.8	" - KARIOBANGI
20.0	19.1	.1363	HU	22.1	" - PARKLANDS
64.0	58.8	.0514	HU	62.0	" - MILIMANI
18.0	9.7	.0056	9.7	9.8	" - NRB. WEST
33.0	21.5	.0050	HU	21.6	" - JAMHURI PARK
30.0	28.1	.0998	HU	31.2	" - NRB. SOUTH
100.0	65.2	.0000	65.2	65.2	NAIROBI LTDM - NAIROBI CENTRAL
43.0	17.9	.0000	17.9	17.9	" - EMBAKASI
17.0	10.9	.0232	11.2	11.2	" - EASTLEIGH
69.0	45.3	.0002	45.3	45.3	" - KARIOBANGI
100.0	77.0	.0017	77.1	77.1	" - PARKLANDS
93.0	88.6	.0528		93.5	" - MILIMANI
60.0	12.4	.0000	12.4	12.4	" - NRB. WEST
30.0	18.9	.0046	19.0	19.0	" - JAMHURI PARK
35.0	31.5	.0727	34.4	34.0	" - NRB. SOUTH
42.0	23.2	.0001	23.2	23.2	" - LANGATA
34.0	18.7	.0004		18.7	" - UTHIRU
15.0	5.6	.0005	5.6	5.6	" - GIGIRI
18.0	3.7	.0000	3.7	3.7	EMBAKASI - NRB. NSC
19.0	11.0	.0085	11.1	11.1	" NRB. CENTRAL
33.0	11.7	.0000	11.7	11.7	" NRB. LTDM
18.0	2.7	.0000	2.7	2.7	" EMBAKASI
15.0	3.2	.0000	3.2	3.2	EASTLEIGH - NRB NSC
20.0	17.9	.1068	22.4	20.0	" - NRB LTDM
10.0	2.6	.0003	2.6	2.6	" - EASTLEIGH
14.0	5.3	.0008	5.3	5.3	KARIOBANGI - NRB. NSC
21.0	19.3	.1149	HU	21.8	" - NAIROBI CENTRA
49.0	39.0	.0183	39.9	39.7	" - NRB LTDM
30.0	15.0	.0002	15.0	15.0	" - KARIOBANGI
10.0	7.1	.0828	8.1	7.7	" - MILIMANI
19.0	10.6	.0062	10.7	10.7	PARKLANDS - NAIROBI NSC.
20.0	18.7	.1263	HU	21.4	" - NAIROBI CENT.
70.0	49.9	.0013	50.0	50.0	" - NAIROBI LTDM.
96.0	34.1	.0000	34.1	34.1	" - PARKLANDS
12.0	7.1	.0292	HU	7.3	" - MILIMANI
8.0	3.0	.0086	HU	3.0	" - JAMHURI PARK
6.0	4.3	.1414	HU	5.0	" - NRB SOUTH
40.0	17.5	.0000	17.5	17.5	MILIMANI - NRB. NSC

Figure 4.4d: Nairobi Network

50.0	43.5	.0414	HU	45.4	MILIMANI - NRB. CENTRAL
70.0	30.4	.0000	30.4	30.4	" - NRB. LTDM
10.0	4.5	.0106	HU	4.5	" - KARIOBANGI
11.0	6.0	.0230	HU	6.1	" - PARKLANDS
68.0	20.8	.0000	20.8	20.8	" - MILIMANI
14.0	8.1	.0186	HU	8.3	" - JAMHURI PARK
26.0	3.0	.0000	3.0	3.0	NAIROBI WEST - NRB. NSC
18.0	6.2	.0001	HU	6.2	" - NRB. CENTRAL
51.0	16.0	.0000	16.0	16.0	" - NRB. LTDM
24.0	2.7	.0000	2.7	2.7	" - NRB. WEST
7.0	1.8	.0024	HU	1.8	" - NRB. SOUTH
20.0	9.7	.0014	9.7	9.7	JAMHURI PARK - NRB NSC
34.0	23.8	.0101	HU	24.0	" - NRB CENTRAL
45.0	32.5	.0071	32.7	32.7	" - NRB LTDM
8.0	4.1	.0342	HU	4.2	" - PARKLANDS
14.0	10.5	.0704	HU	11.3	" - MILIMANI
54.0	12.7	.0000	12.7	12.7	" - JAMHURI PARK
27.0	16.8	.0057	16.9	16.9	NAIROBI SOUTH - NRB. NSC
32.0	28.0	.0665	HU	30.0	" - NRB. CENTRAL
45.0	27.5	.0006	27.5	27.5	" - NRB. LTDM
6.0	2.6	.0351	HU	2.7	" - PARKLANDS
54.0	13.1	.0000	13.1	13.1	" - JAMHURI PARK
54.0	9.7	.0000	9.7	9.7	" - NRB SOUTH
10.0	6.0	.0433	6.3	6.3	LANG'ATA - NRB NSC
32.0	23.3	.0170	23.8	23.7	" - NRB. LTDM
10.0	5.2	.0225	5.3	5.3	" - LANGATA
3.0	1.0	.1000	1.1	1.1	UTHIRU - NRB NSC
9.0	1.8	.0001	1.8	1.8	" - NRB CENTRAL
16.0	8.9	.0102	9.0	9.0	" - NRB. LTDM
15.0	9.2	.0227	9.4	9.4	" - UTHIRU
15.0	9.2	.0227	9.4	9.4	" - UTHIRU
15.0	9.1	.0213	9.3	9.3	KIKUYU - NRB LTDM
10.0	1.9	.0000	1.9	1.9	KABETE - KARIOBANGI
28.0	22.9	.0505	24.9	24.1	KABETE - NRB. LTDM

In order to evaluate the extent to which the designed grade of service is met on the routes the various networks are considered case by case.

4.3.1 Coast Network

In the coast network the offered grade of service in the majority of routes is equal or better than the designed value. The three routes which result in unacceptable blocking of traffic are:

Route from Mombasa to Bamburi with congestion of 11%

Route from Mombasa to Changamwe with Congestion of 4%

The own-exchange route for Diani Beach with congestion of 4%.

4.3.2 Nakuru Network

In the Nakuru network approximately 50% of the routes do not meet the designed grade of service. Significant congestion is encountered on four routes namely:

Route from Nairobi to Nakuru with congestion of 7%

Route from Nakuru to Nairobi with congestion of 7%

Route from Nakuru to Eldoret with congestion of 9%

Route from Eldoret to Nakuru with congestion of 10%

Other congested routes are:

Route from Nairobi to Eldoret with congestion of 2%

Route from Eldoret to Nairobi with congestion of 3%

4.3.3 Kisumu Network

Eight routes out of the total twenty five routes have congestion in excess of the designed grade of service of 0.01.

These routes are:-

Route from Kisumu to Kericho with congestion of 5%

Route from Kisumu to Nairobi with congestion of 7%

Route from Kisumu to Kakamega with congestion of 17%

Route from Kakamega to Nairobi with congestion of 6%

Route from Kakamega to Kisumu with congestion of 6%

Route from Kericho to Kisumu with congestion of 5%

Route from Nakuru to Kisumu with congestion of 6%

Route from Nakuru to Kericho with congestion of 15%

4.3.4 Nyeri Network

Of the ten routes in the Nyeri network only one route from Nyeri to Embu is found to be congested.

4.3.5 Nairobi network

This is a network comprising 17 switching systems and has a large number of High Usage routes. A few of the routes in this network were found to have unacceptable congestion levels:-

Route from Nairobi Central to Nairobi NSC with 5% congestion

Route from Nairobi Ltdm to Eastleigh with 5% congestion

Route from Nairobi Ltdm to Milimani with 5% congestion

route from Nairobi Ltdm to Nairobi South with 7% congestion.

Route from Eastleigh to Nairobi NSC with 10% congestion

Route from Kariobangi to Nairobi Ltdm with 2% congestion.

Route from Kariobangi to Milimani with 8% congestion

Route from Langata to Nairobi NSC with 4% congestion

Route from Langata to Nairobi Ltdm with 2% congestion

Route from Uthiru to Nairobi NSC with 10% congestion

Route from Kikuyu to Nairobi Ltdm with 2% congestion

Route from Kabete to Nairobi Ltdm with 5% congestion

4.4 High Usage Routes

High Usage routes where no congestion is recordable since excess traffic overflows into a lower priority route have been indicated. The entries in the column 'congestion' for these routes indicate the blocking that would exist if the routes were not high usage.

4.5 Comparison of Conventional Methods of obtaining A_o with the 'Erlang B' Programme.

The normal practice within the Kenya Post and Telecommunication Corporation is to estimate offered traffic on a given route by use of tables. In particular the tables from "TELEVERKETS CENTRALFORVALTNING, Stokholm are used. The tables can be used for traffic ranging between 0.1 - 80.0 erlangs and for routes containing between 1-105 circuits.

The values of offered traffic calculated by use of these tables are shown on the 4th column, and shows very close correspondence to those values resulting from the Programme 'Erlang B'. The biggest difference in the two values is for the route for traffic flowing from Bamburi to Mombasa GSC, where A_o obtained from calculations using tables is 19.4 erlangs; and A_o obtained by the Programme is 22.4 erlangs. This represents a difference of 3 erlangs.

Conclusions from the Results

The programme 'ERLANG B' developed in this chapter gives a good estimate for the offered traffic given the number of circuits and the carried traffic measured on the route.

The effectiveness of the programme is deduced by observing that the largest deviation of A_0 from that obtained using traffic tables is approximately 3 erlangs. All other deviations are much smaller than the 3 erlangs observed in the worst case.

Because of the assumptions made to obtain B_1 in equation 4.3a, B_1 may not always represent the exact congestion encountered. However, it can be stated that in all cases the congestion is greater than or equal to B_1

that is congestion $\geq B_1$

The programme 'ERLANG B' is thus a sufficient tool that can be used to assess the status of a network consisting of relatively large automatic switches linked by circuit groups, each of known sizes carrying known traffic. By status it is meant that each link can be categorized as congested or not congested. The traffic that is blocked as a result of this congestion can be estimated. On heavily congested routes however the resulting estimates of offered traffic are used with caution bearing in mind that a possible deviation of upto 3 erlangs could exist.

From the results of section 4.3 it is also concluded that a fair percentage of the links in the telecommunications network are congested to proportions which would be unacceptable as compared to the design values. The service offered on these routes is of lower grade and causes significant blocking of telecommunications traffic. The percentage of the congested to non-congested routes varies from network to network as follows:

Coast network	13%
Nakuru network	50%
Kisumu network	32%
Nyeri network	10%
Nairobi network	14%

Overall an approximate 24% of all the links connecting automatic exchanges are considered to be offering a grade of service below that designed.

CHAPTER FIVE

DEMAND FORECASTS

In an ideal telecommunications network where no restrictions exist, traffic forecasting and planning would ensure that demands for telecommunication service are accurately foreseen and satisfied as they arise. In a developing country like Kenya however, the time lag between identification of need for service and the ability to meet this need is considerable. In some cases the time lag has been known to exceed 10 years as a result of economic constraints. This means that accurate forecasts are of utmost importance if the necessary plant is to be available before existing capacity is exhausted. Further to this errors in forecasting can prove very costly for a telecommunications organisation. For example over estimation results in unnecessary investment in expensive equipment which earns no revenue. Under-estimation on the other hand results in losses of revenue that could be earned and renders the network inadequate.

A further drawback in a developing network is the fact that existing requirement for service is often not satisfied. This gives rise to a situation where at any one time there are demands on the network that cannot be served. By only considering existing users of the network for forecasting purposes these demands are hidden causing innaccurate forecasts. It therefore becomes necessary to assess the network to determine to what extent the requirements on it are met before forecasting for future growth.

5.1 ASSESSMENT OF THE NETWORK FOR UNSATISFIED DEMAND

The demand and growth characteristics of telecommunication service varies from region to region and is dictated to a certain extent by various exogeneous factors such as population growth and distribution, income, industrialisation of the area, stage in development and the general occupation of the community among others. A general assessment of the whole network would thus give misleading results.

In this section the five major towns (Nairobi, Mombasa, Kisumu, Nakuru, Nyeri) have been considered separately to determine the manner in which demand for service has been satisfied. Reference to Figure 2.6 shown that these are Area Switching Centres (A.S.C.) regions and due to the heirarchical nature of the Kenyan network their growth and demand characteristics would be representative of the characteristics of the Group Switching Centres (G.S.C.) and End Offices (E.O.) connected to them.

5.1.1. Data Presentation

For each of the stations the necessary data was obtained and recorded in a table, as illustrated in the tables of Figure 5.1.

The first column gives the year under consideration. In the second column the number of connected users is entered. This represents the number of actual telephone pairs in use and no categorisations are given. The third column has the number of waiting users in the area and represents the unsatisfied demand. The fourth column is a total of the second and third column and is considered as the 'total demand' for service in the region. This represents the number of would be users in an ideal situation where unlimited plant is available and telecommunication service is provided on request. The final column indicates what percentage of the total demand is contributed by the waiting users.

KISUMU

Year (a)	Connected Users (b)	Waiting Users (c)	Total Demand (b+c)	$e = \frac{c}{d}$ %
1965	729	53	782	6
1966	755	84	839	10
1967	735	152	887	17
1968	860	138	998	14
1969	1051	162	1113	15
1970	1107	165	1272	13
1971	1276	382	1658	23
1972	1384	593	1977	30
1973	1711	258	1969	15
1974	1829	447	2276	20
1975	1904	651	2555	25
1976	2162	568	2730	21
1977	2253	431	2884	16
1978	2292	586	3127	19
1979	2490	650	3140	21
1980	2868	621	3489	18
1981	3205	706	3911	18
1982	3424	1045	4469	32
1983	3594	1163	4757	24

Avg. = 18%

Figure 5.1a: Kisumu

MOMBASA

Year (a)	Connected Users (b)	Waiting Users (c)	Total Demand d = b+c	$e = \frac{c}{d}$ %
1965	4378	140	4518	3
1966	4532	318	4850	6
1967	4724	478	5202	9
1968	4951	649	5600	12
1969	5260	532	5797	9
1970	5382	1249	6631	19
1971	6125	1337	7462	18
1972	6917	1275	8192	16
1973	7026	1886	8915	21
1974	7252	2360	9612	25
1975	7663	2545	10.008	25
1976	8408	3247	11,655	28
1977	9357	1921	11,278	17
1978	9770	3045	12,815	24
1979	10,255	3897	14,152	28
1980	10,643	5035	15,678	32
1981	11,719	5474	17,193	32
1982	12,278	6822	19,100	36
1983	12,926	6505	19,431	33

Avg = 21%

Figure 5.1b.: Mombasa

NAKURU

Year (a)	Connected Users (b)	Waiting Users (c)	Total Demand d = b+c	$e = \frac{c}{d}\%$
1965	1137	10	1147	1
1966	1186	47	1233	4
1967	1238	74	1312	6
1968	1236	107	1343	8
1969	1217	136	1353	10
1970	1255	251	1506	17
1971	1561	266	1827	15
1972	1756	282	2038	14
1973	1754	289	2043	14
1974	1822	490	2313	21
1975	1931	716	2547	27
1976	2353	365	2718	13
1977	2658	255	2913	9
1978	2847	365	3212	11
1979	2897	583	3480	17
1980	2951	1031	3982	26
1981	3078	1739	4817	36
1982	3132	2014	5146	39
1983	3558	2880	6438	45

Avg = 18%

Figure 5.1c: Nakuru

NYERI

Year (a)	Connected Users (b)	Waiting Users (c)	Total Demand d = b+c	$e = \frac{c}{d}\%$
1965	862	152	1014	15
1966	870	198	1068	19
1967	932	178	1110	16
1968	1014	248	1262	20
1969	1043	219	1262	17
1970	1076	343	1419	24
1971	1262	402	1664	24
1972	1524	273	1797	15
1973	1683	308	1991	15
1974	2066	343	2409	14
1975	2266	847	3113	27
1976	2517	1091	3608	30
1977	2937	1751	4688	37
1978	3034	1845	4879	38
1979	3398	1865	5263	35
1980	3916	2727	6643	41
1981	4022	3598	7620	47
1982	4500	4691	9191	51
1983	5072	4992	10,064	50

Avg = 28%

Figure 5.1d: Nyeri

NAIROBI (INDUSTRIAL AREA)

Year (a)	Connected Users (b)	Waiting Users (c)	Total Demand d = b+c	$e = \frac{c}{d}\%$
1965	1189	118	1307	9
1966	1255	448	1703	26
1967	1307	579	1886	31
1968	1425	510	1935	26
1969	1985	465	2450	19
1970	2388	519	2907	18
1971	2650	1134	3784	30
1972	3008	1720	4788	36
1973	4352	2115	6467	33
1974	4410	2019	6429	31
1975	4564	2441	6490	35
1976	4498	2030	6528	31
1977	4579	2004	6583	30
1978	4758	2356	7114	33
1979	5028	4055	9083	45
1980	5142	4227	9363	45
1981	5303	5390	10,693	50
1982	5809	6292	12,101	52
1983	6309	6912	13,221	52

Avg = 33%

Figure 5.1e: Nairobi Industrial Area

NAIROBI (RESIDENTIAL AREA)

Year (a)	Connected Users (b)	Waiting Users (c)	Total Demand d = b+c	$e = \frac{c}{d}\%$
1965	1121	71	1192	6
1966	1127	157	1284	12
1967	1151	392	1543	25
1968	1397	129	1626	8
1969	1598	245	1843	13
1970	1629	388	2017	19
1971	1831	243	2074	11
1972	2226	525	2751	19
1973	2328	678	3006	23
1974	2330	1083	3418	32
1975	2377	1387	3764	37
1976	2755	754	3509	21
1977	2893	949	3842	25
1978	2888	1326	4214	31
1979	3267	1380	4647	30
1980	3313	1770	5083	35
1981	3407	3277	6684	50
1982			7080	
1983	4129	4037	8166	50

Avg = 25%

Figure 5.1f: Nairobi Residential Area

Figure 5.2a: KISUMU

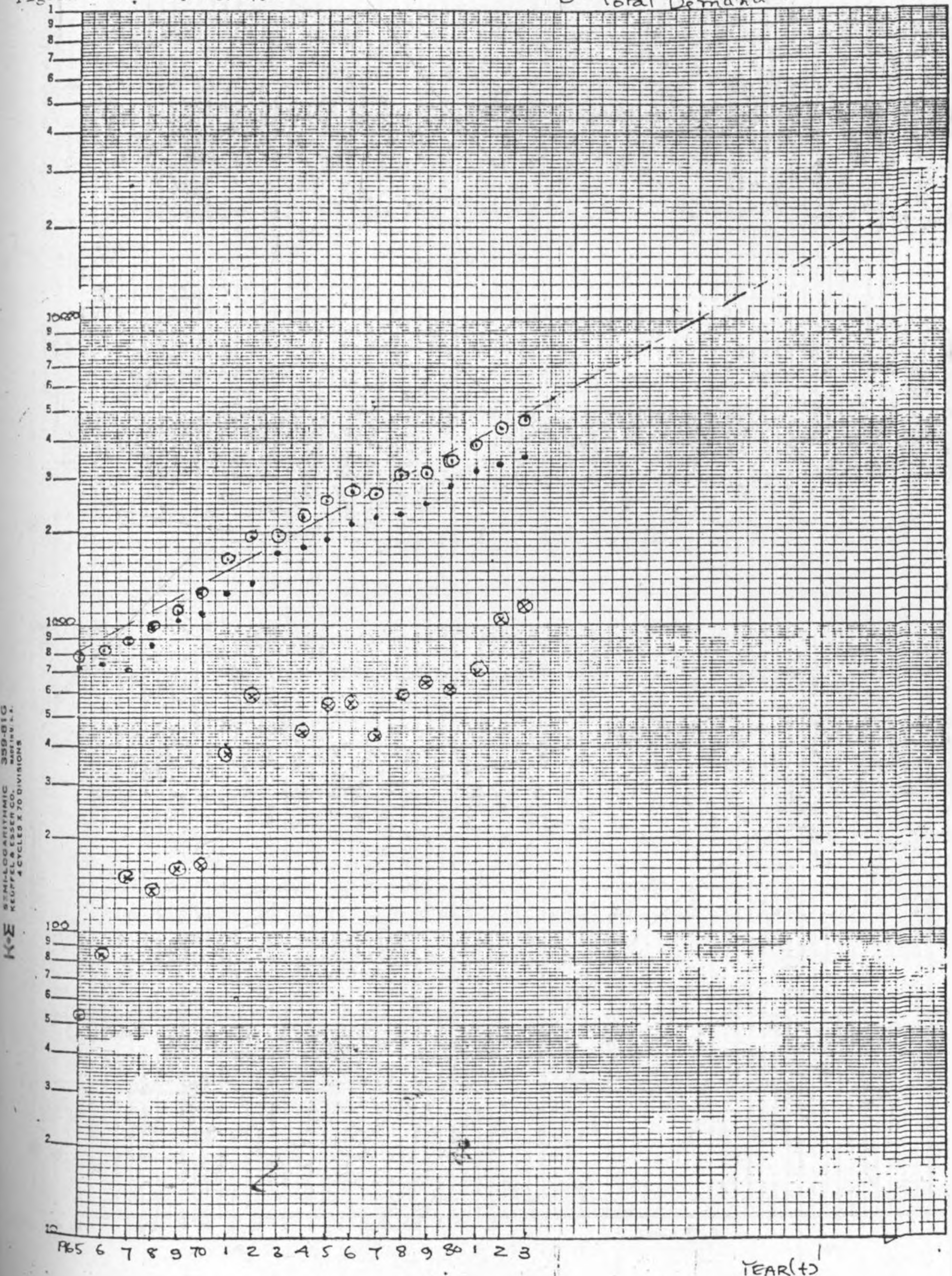


Figure 5.2b: MOMBASA

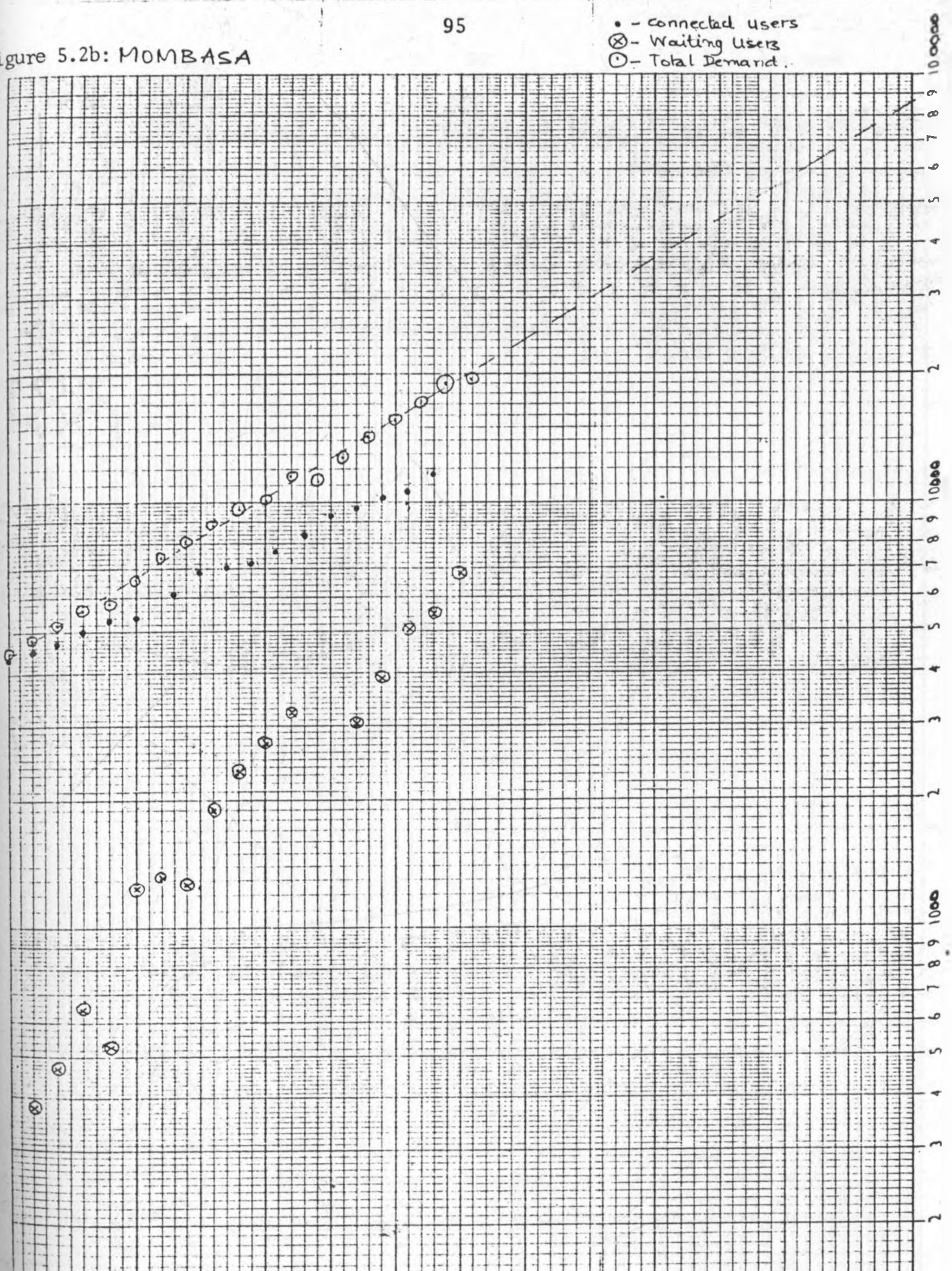


Figure 5.2c: NAKURU

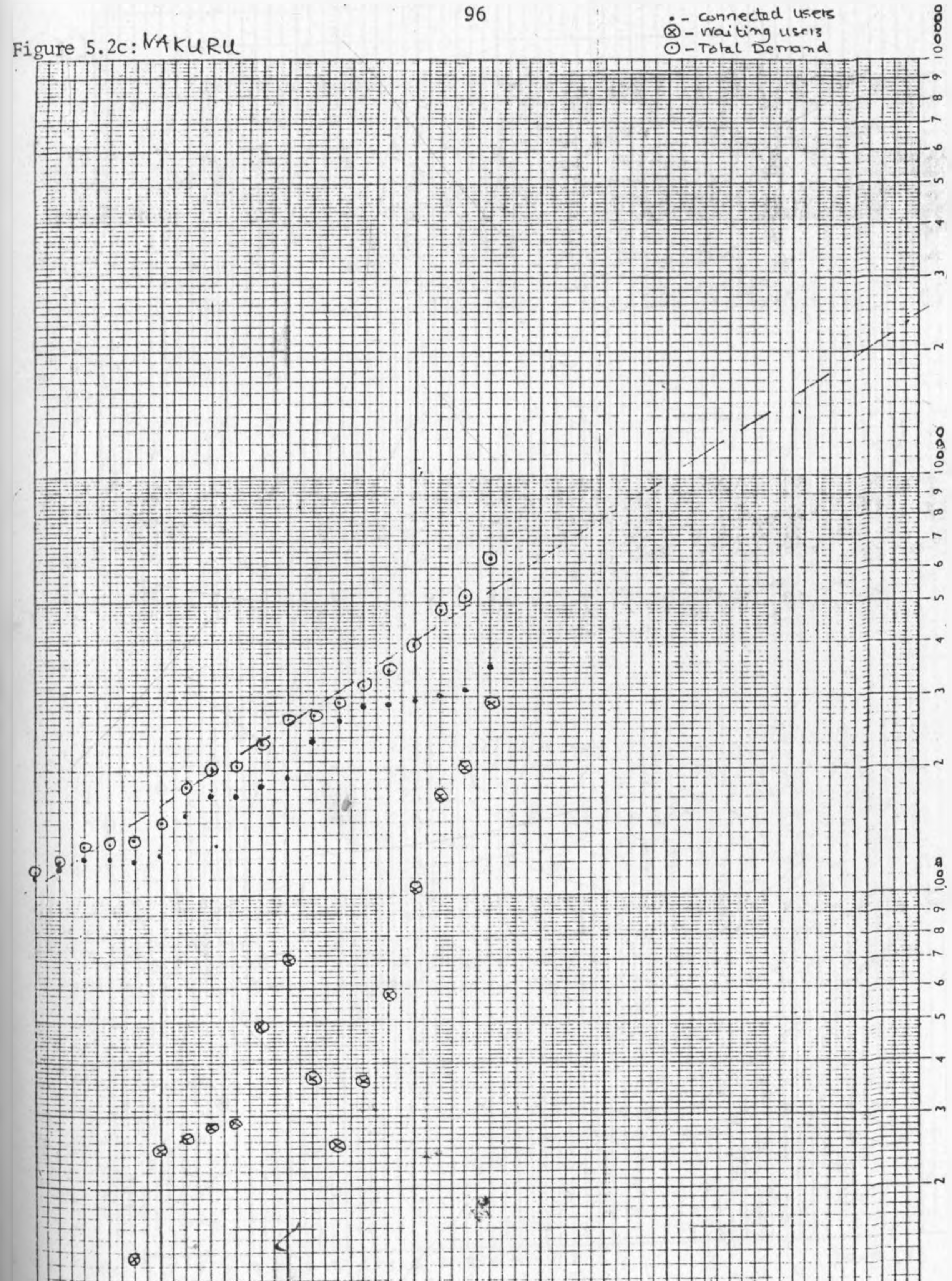


Figure 3.2d:

NYERI

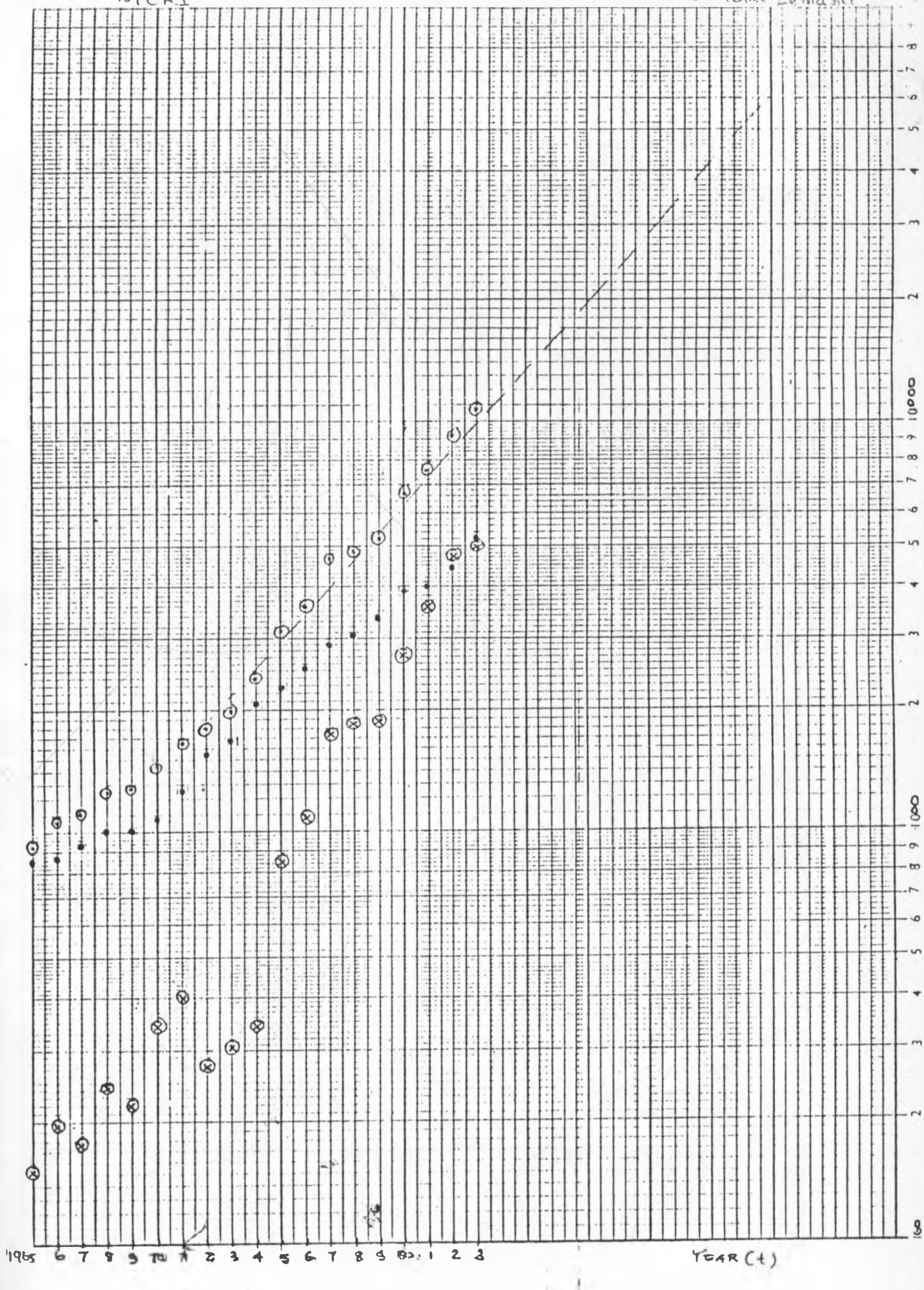


Figure 5.2e:

NAIROBI INDUSTRIAL AREA

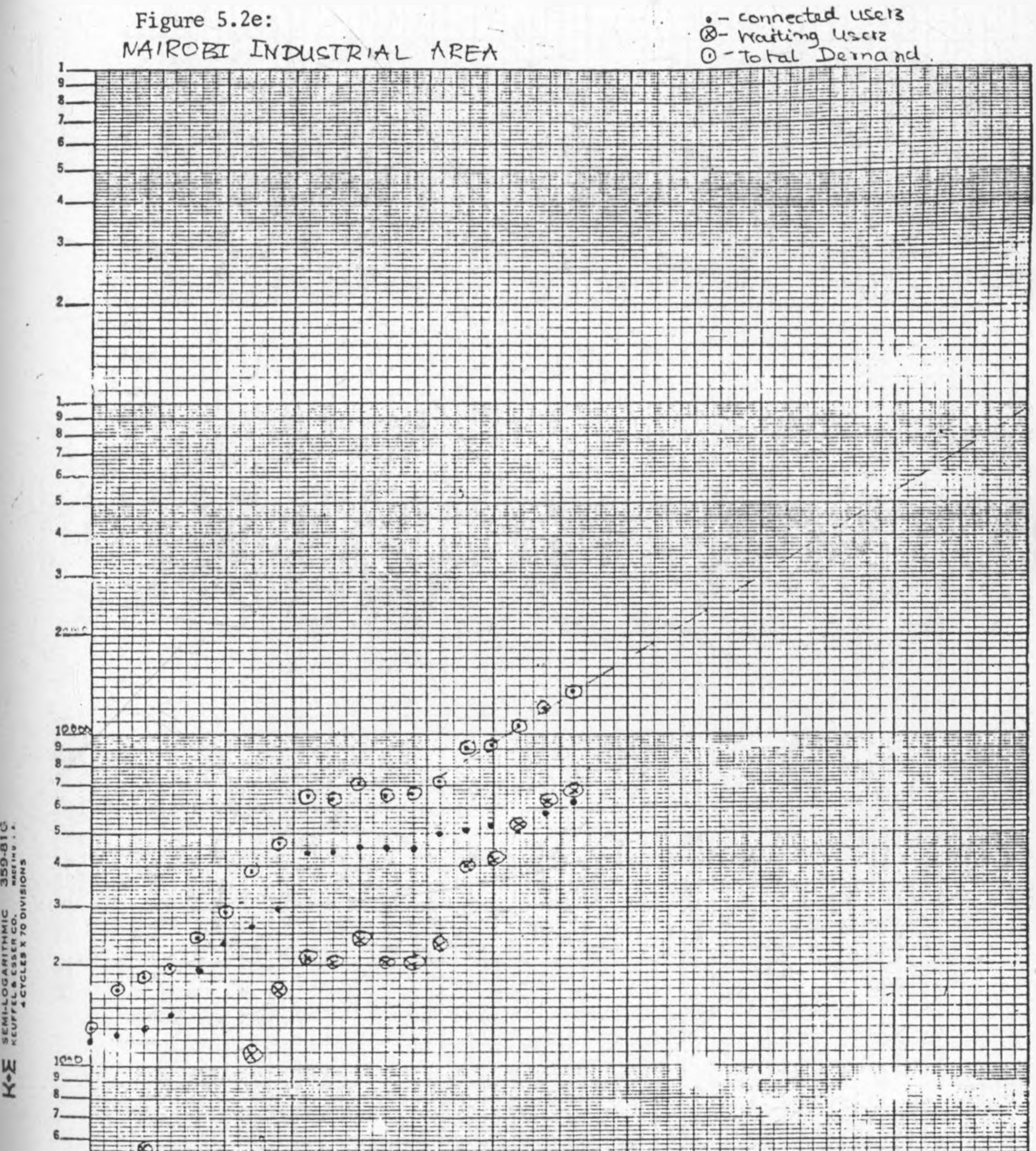
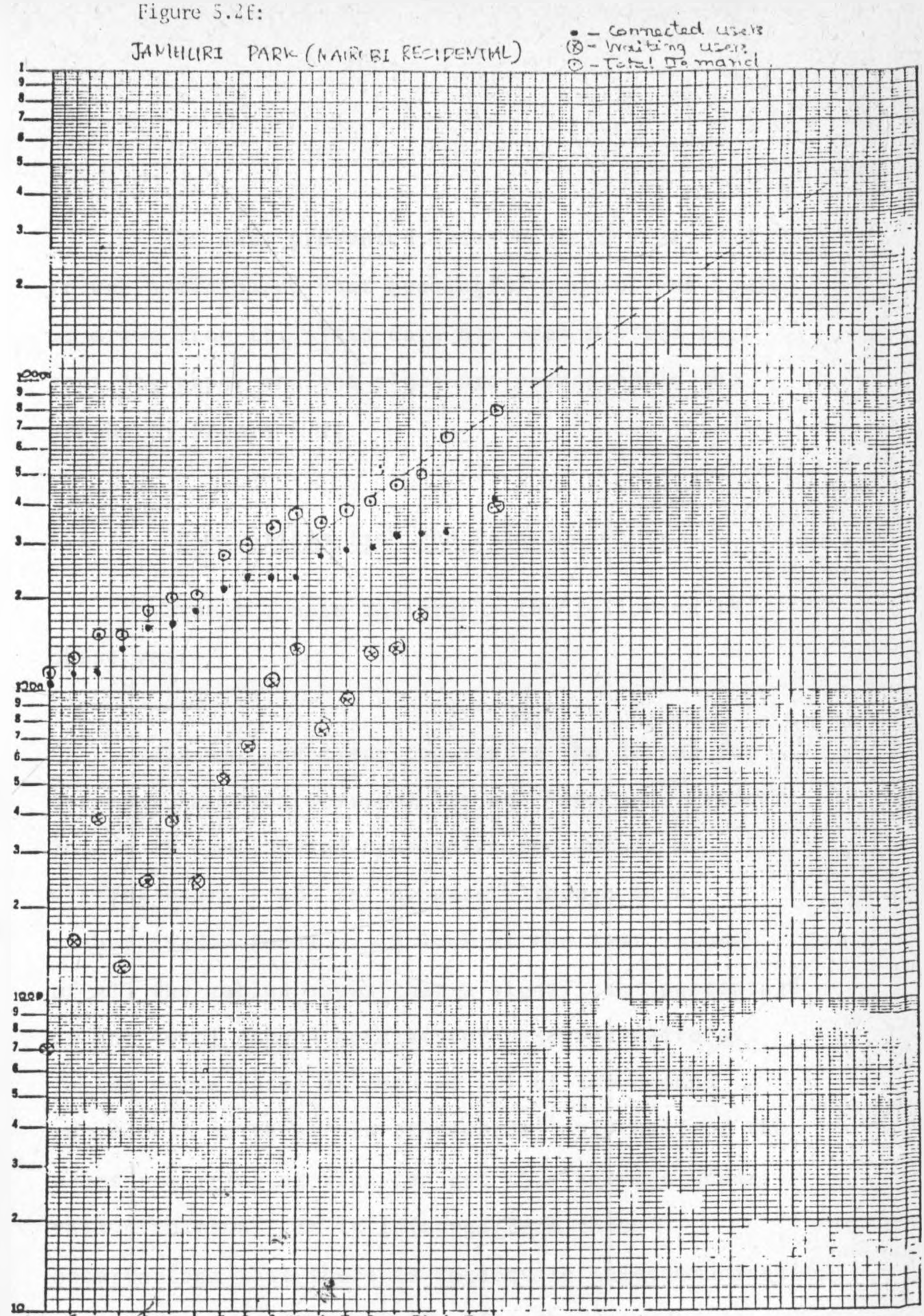


Figure 5.2f:

JAMHURI PARK (NAIROBI RESIDENTIAL)



The data presented dates back 19 years and it was anticipated that meaningful conclusions could be drawn from it. This data has been plotted on semi-log paper and the plots are presented in the graphs of Figure 5.2.

5.1.2. Observations from the Data and Plots

From the data and graphs the following is obeserved:-

In all the areas considered the demand for telecommunication services has not been met. Infact in the 19 year period considered the number of waiting users tends to increase although in a rather random fashion. A look at the last column of all the tables shows that a significant percentage of the total demand consists of unserved waiters. In the worse cases as much as 50% of the demand represents waiters. In otherwords only half of the users requiring service can get this service under this situation. It is inferred from these observations that there is inadequate telecommunication plant in the network to cater for the demand.

One reason for this inadequacy is the lack of revenue. However another reason could be that the demand as it exists was not foreseen, in other words there were no accurate forecasts to enable the right amount of plant to be availed. The fact that the unsatisfied demand tends to increase with time in all areas points to the fact that forecasts do not take this hidden demand into consideration.

A comparison of the 5 areas reveals that the situation is worst in Nairobi's Industrial area where over the 19 year period an average of 33% of demand is attributed to waiting users. This would be expected as growth in such an area is bound to be more rapid than in a residential area, since a household need only have one telephone, but an industry's requirement for telephones grows with the growth of the plant. Nakuru and Kisumu are perhaps better served with an average of 18% of demand being from waiters.

A look at the graphs of connected users vs time shows that the growth 'flattens' out when the 'waiters' graph climbs steeply. A good illustration of this is the Nairobi Residential area case, between say 1972 - 1981. In this period of time the number of users grew from 2226 to 3407 representing a growth of 1181 whereas the number of waiting users grew from 525 to 3277, a growth of 2752. An explanation for this is that during this period the plant had been exhausted and no more users could be provided with service. But the requirement for service is not dependent on availability of plant and continued to be registered.

Similar behaviour can be seen in the other cases as well. Consider Nakuru in the period 1970 - 1982. We notice that in the period between 1972 - 1975 the connected users' graph remains fairly flat whereas that of 'waiters' experiences a steep climb. Between 1975 and 1977 a climb in the connections graph is accompanied by a fall in the waiters' graph, and between 1977 to 1982 the waiters increase steadily while the number of connections remains fairly constant.

The above illustrates the fact that accumulation of waiting users is inversely dependent on the capability of the network to accommodate new users.

As previously mentioned the demand is considered to be the additive combination of the connected users and the waiting users. A look at the graphs of demand/time for Kisumu, Nakuru, Mombasa and Nyeri reveals that the plots approximate to a straight line on semi-logarithmic paper. The plots for the Nairobi area reveal deviations from a straight line. The approximately straight line plots indicate that the demand grows in an exponential fashion[2].

5.1.3 Choice of Model for the growth of Demand for Telecommunications Service

The simplest exponential model that could be used to describe the growth of the demand for telecommunications service would be of the form

$$y = e^{a_1 + a_2 t} \qquad \ldots\ldots 5.1$$

where y = demand

t = time in years.

The growth rate of any model as defined for one period of time is

$$R \triangleq \frac{y_{t+1} - y_t}{(t+1-t)y_t} = \frac{y_{t+1} - y_t}{y_t} \qquad \ldots\ldots 5.2$$

where y_t = demand at time t

The limiting growth rate for a continous function is given by

$$R(t) \;=\; \lim_{\Delta t \to 0} \frac{y(t + \Delta t) - y(t)}{\Delta t \;\; y(t)}$$

$$= \frac{dy(t)}{dt} \,/y(t), \qquad \ldots\ldots \; 5.3$$

Thus for the exponential model the growth rate would be

$$R(t) \;=\; \frac{d(e^{a_1+a_2t})}{dt} \cdot \left[\frac{1}{e^{a_1 + a_2t}}\right] \qquad \ldots\ldots \; 5.4$$

$$= \frac{e^{a_1 + a_2t}}{e^{a_1 + a_2t}} \cdot a_2 \;=\; a_2 \;=\; \text{constant}$$

This suggests that constant growth would be expected and may not always be absolutely true. Another model that could be used and that takes care of the variabilityof the growth rates is the logistic growth function[2]

$$y(t) \;=\; \frac{k}{1 + \exp\,(a_1 + a_2t)} \qquad \ldots\ldots \; 5.5$$

where

k = constant representing an upper limit to growth.

A graph of a logistic growth curve is illustrated below in Figure 5.3.

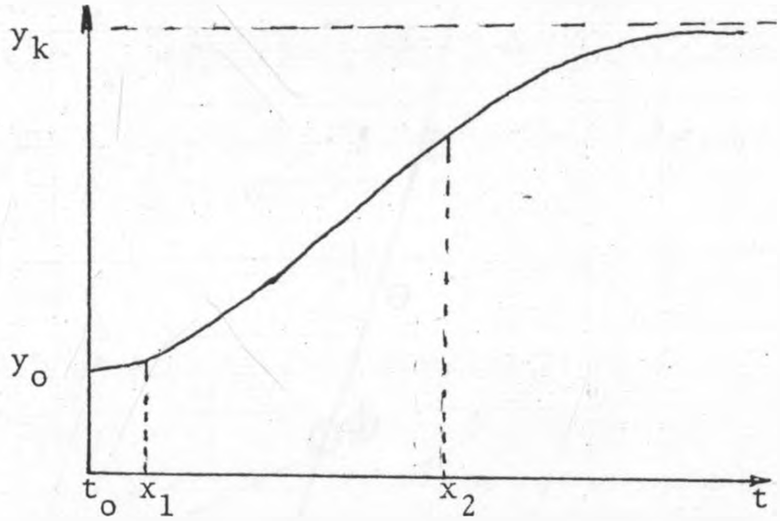


Figure 5.3: Logistic Growth Curve

For smaller values of t the function shows exponential growth. As t increases y(t) approaches the saturation value y_k.

A look at the set of graphs in Figure 5.4 reveals the fact that in all the areas, the growth is in the exponential portion of the logistic growth curve, (that is between X_1 and X_2) and does not approach saturation. For this reason in the forecast period under consideration the growth of demand can be considered exponential, and the model

$$y = e^{a_1 + a_2 t}$$

is adequate.

Figure 5.4a:

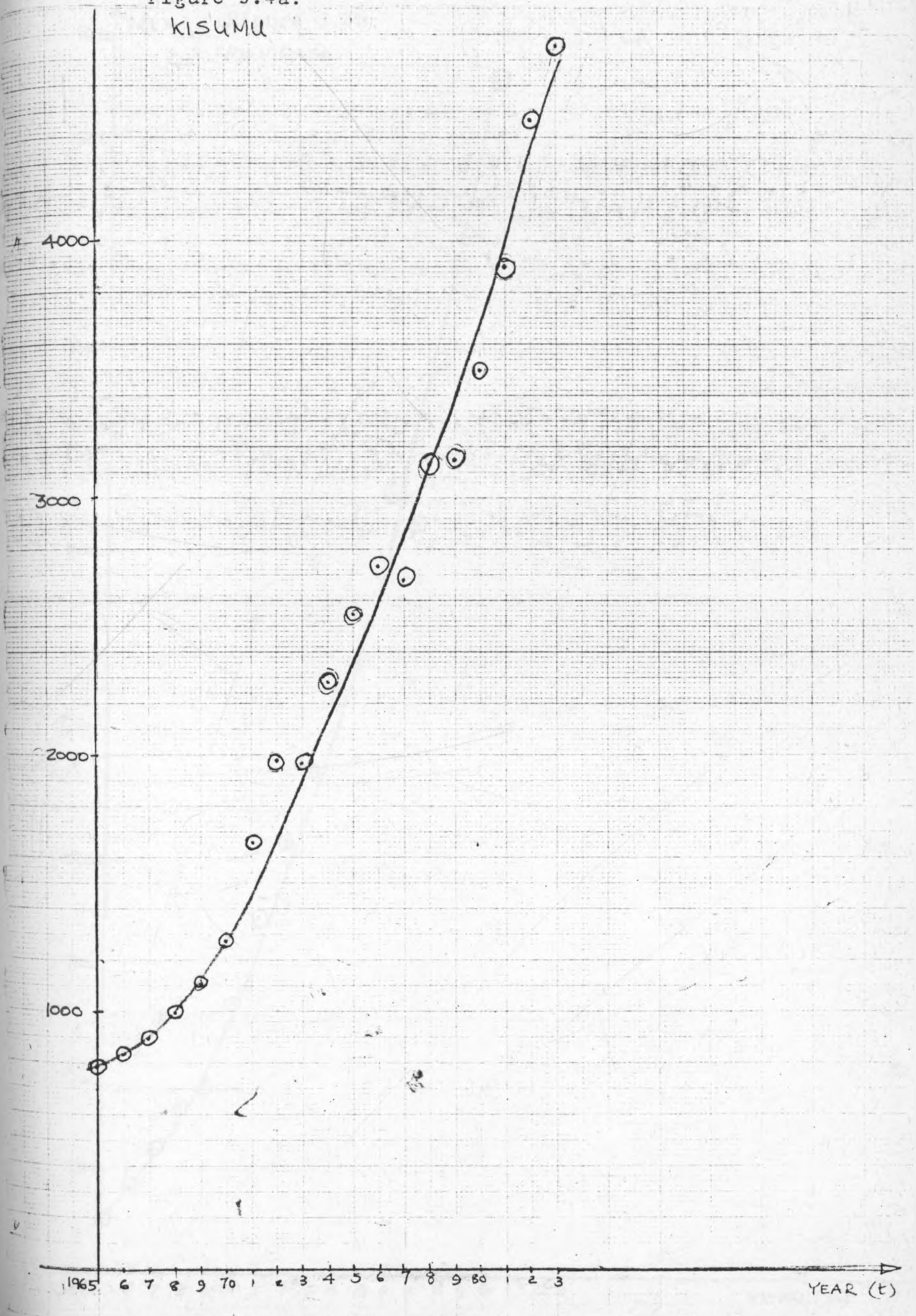
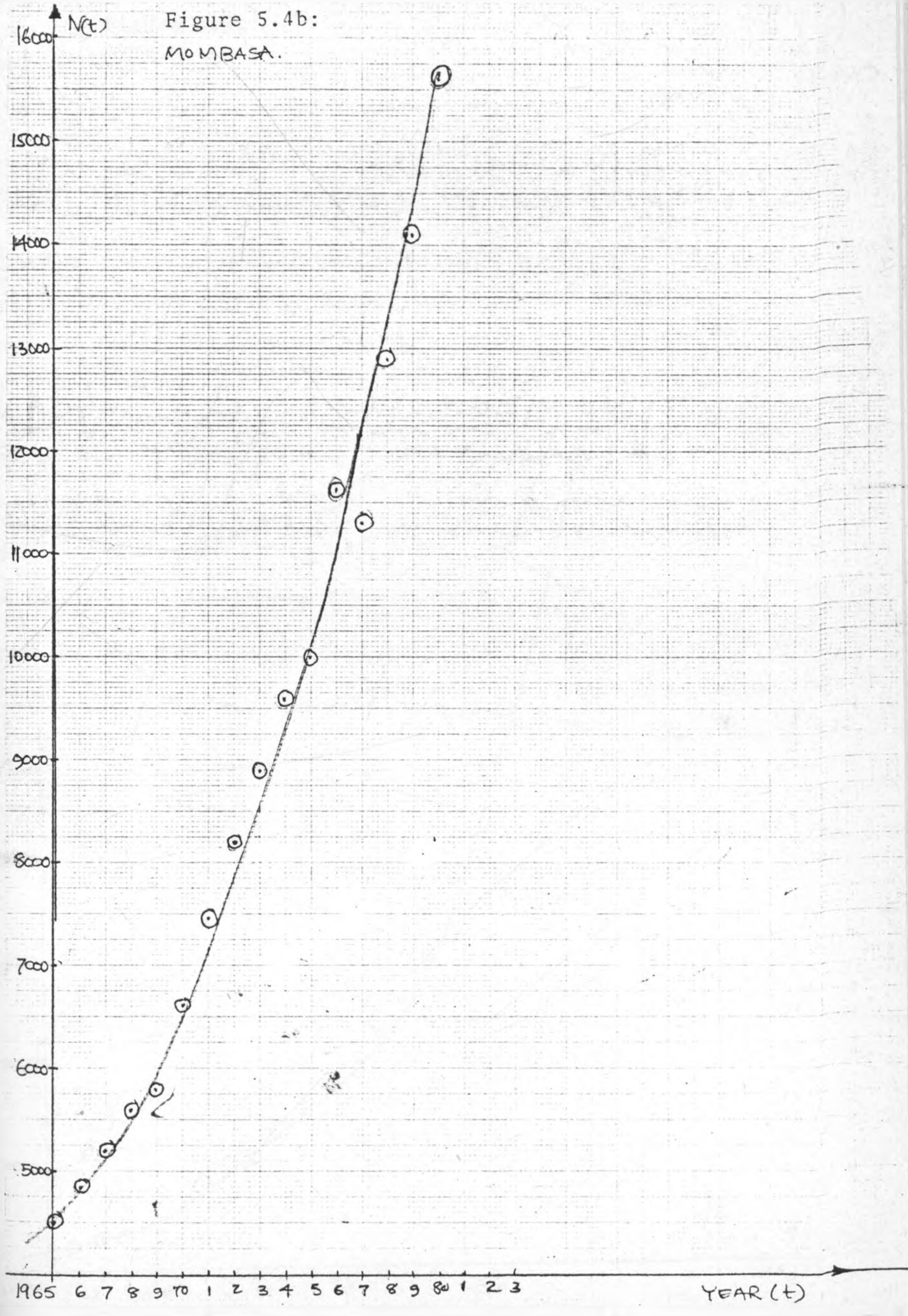

KISUMU
4000
3000
2000
1000
1965
6
7
8
9
70
1
2
3
4
5
6
7
8
9
80
1
2
3
YEAR (t)

Figure 5.4b:

MOMBASA.



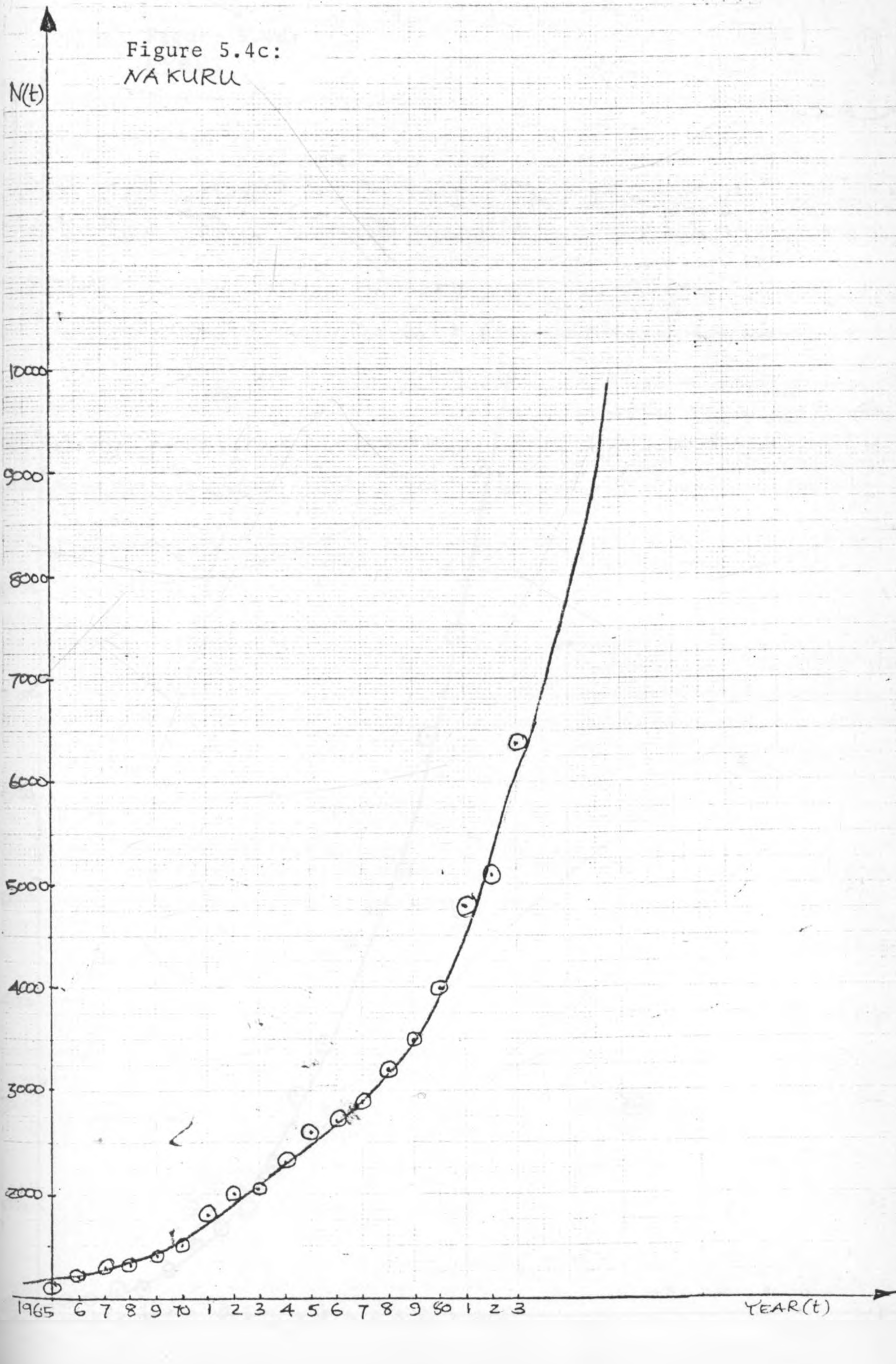
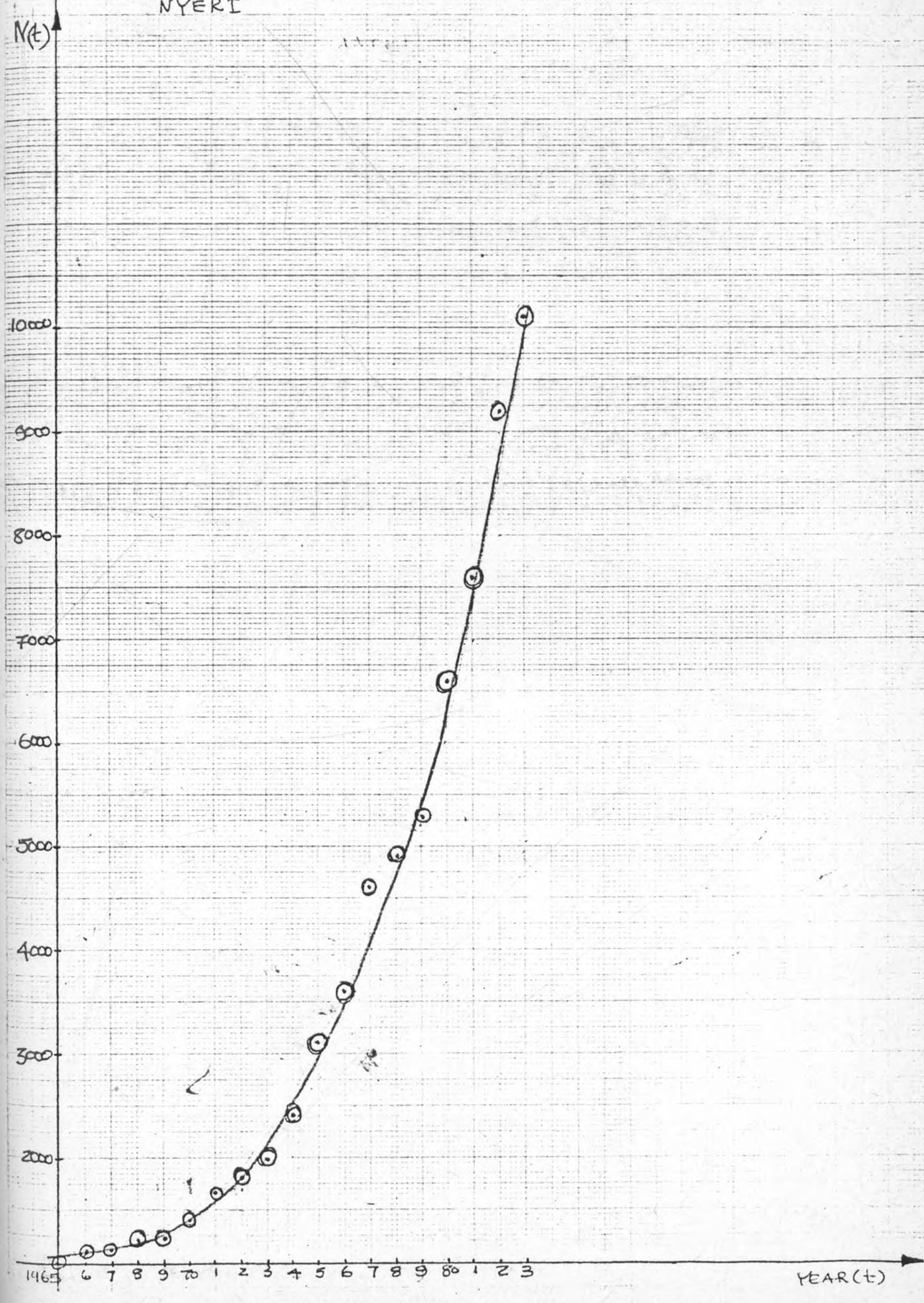


Figure 5.4c:
NAKURU
N(t)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1965 6 7 8 9 70 1 2 3 4 5 6 7 8 9 80 1 2 3
YEAR(t)

Figure 5.4d:
NYERI



NAIROBI (INDUSTRIAL AREA): Figure 5.4e

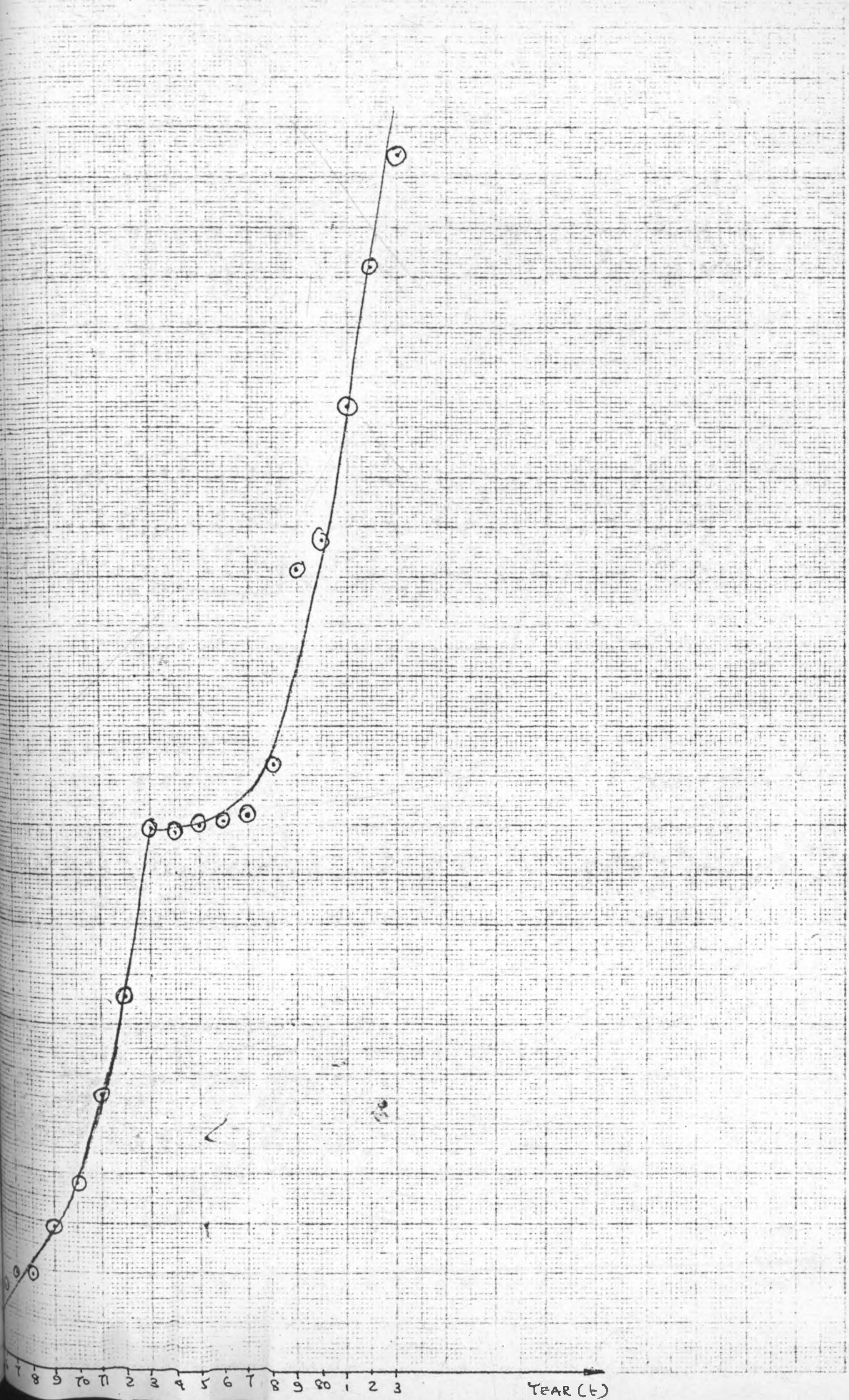
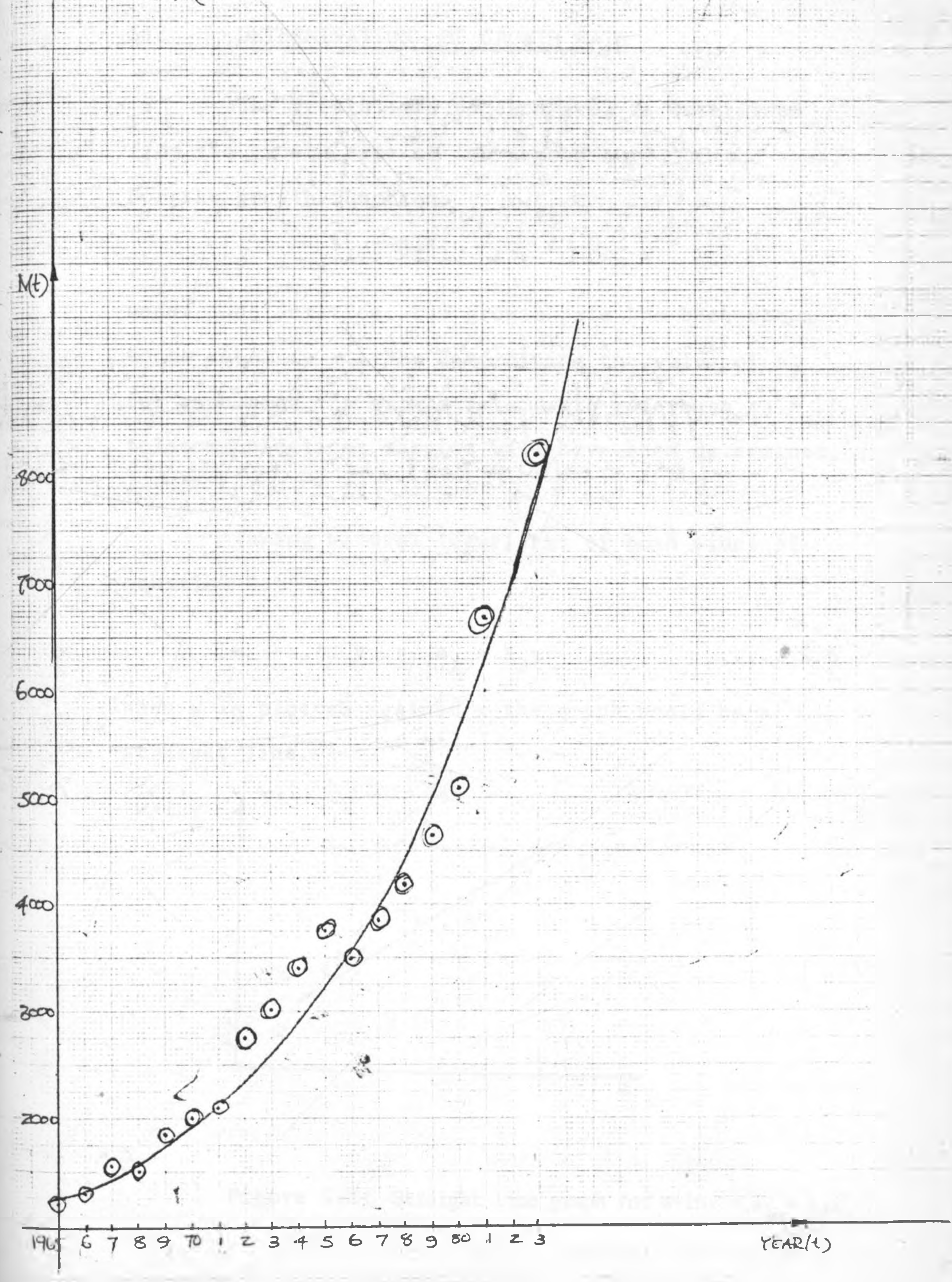


Figure 5.4f:

NAIROBI (A RESIDENTIAL AREA)



5.2 DETERMINATION OF GROWTH RATE

The growth rate of each area is determined from the growth rate of the demand curve of the area. For the growth function

$$y = e^{a_1 + a_2 x}$$

under consideration, the growth rate has been shown to be equal to a_2. By determining the value of a_2 for each area the growth rate, with reference to telecommunications service will have been determined.

Taking natural logarithms of both sides of equation 5.1

$$w = \ln y = a_1 + a_2 x \qquad \ldots\ldots 5.6$$

When w is plotted against x the graph would be a straight line.

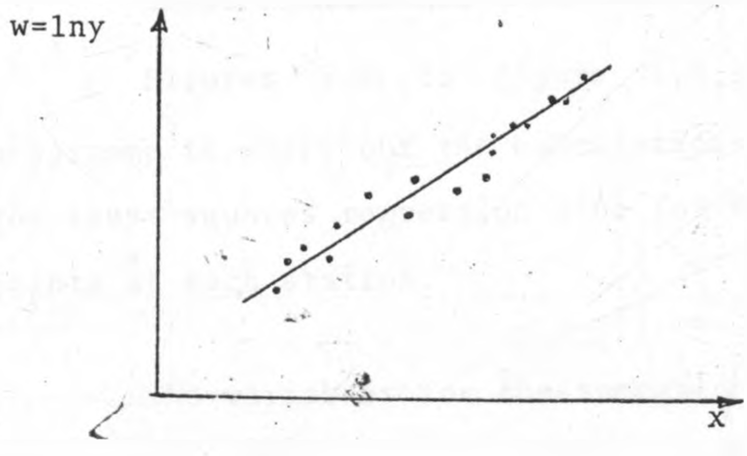


Figure 5.5: Straight line graph for $w = \ln y = a_1 + a_2 x$

For each of the five areas there are 19 data points which relate the demand $N_1(t)$, to time x (in years). The problem to be solved is that of finding a linear equation for a line passing through most or all the points on a plot of w against x where

$$w = \ln y \qquad \ldots\ldots 5.7$$

We note that the data points are obtained from statistical data and cannot be considered absolutely accurate. Some error is expected. We seek to find the best fit line, by which is meant the line for which the error is minimum. The method employed is the least squares regression method whose principles are outlined in Appendix 1.

5.2.1 Computer Programme - Least Square Regression

Figures 5.6 to Figure 5.9 show a Fortran programme to carry out the calculations to obtain the least squares regression line for the 19 data points at each station.

The variables for the summation terms have been choses as:-

$$SUM(1) = \sum_{i=1}^{19} x_i$$

$$SUM(2) = \sum_{i=1}^{19} x_i^2$$

$$RIGHT(1) = \sum_{i=1}^{19} w_i$$

$$RIGHT(2) = \sum_{i=1}^{19} x_i w_i$$

These summations form the coefficients of an array MATRIX. The programme begins by clearing all the summing locations, then enters a DO loop to read all the 19 data points (x_i, y_i) in succession. For each of the data points the term W_i is evaluated and 4 summation terms formed. The data is accessed from an input file designated "DATIN'. Once all summation terms have been formed the programme places each summation term in the appropriate coefficient position. With the matrix thus correctly formed the programme calls the subroutine GAUSS (Figure 5.10) to solve for the coefficients of the matrix (A) . The value of the coefficient A2 is then printed into an output file 'OUTPUT' (Figure 5.11).

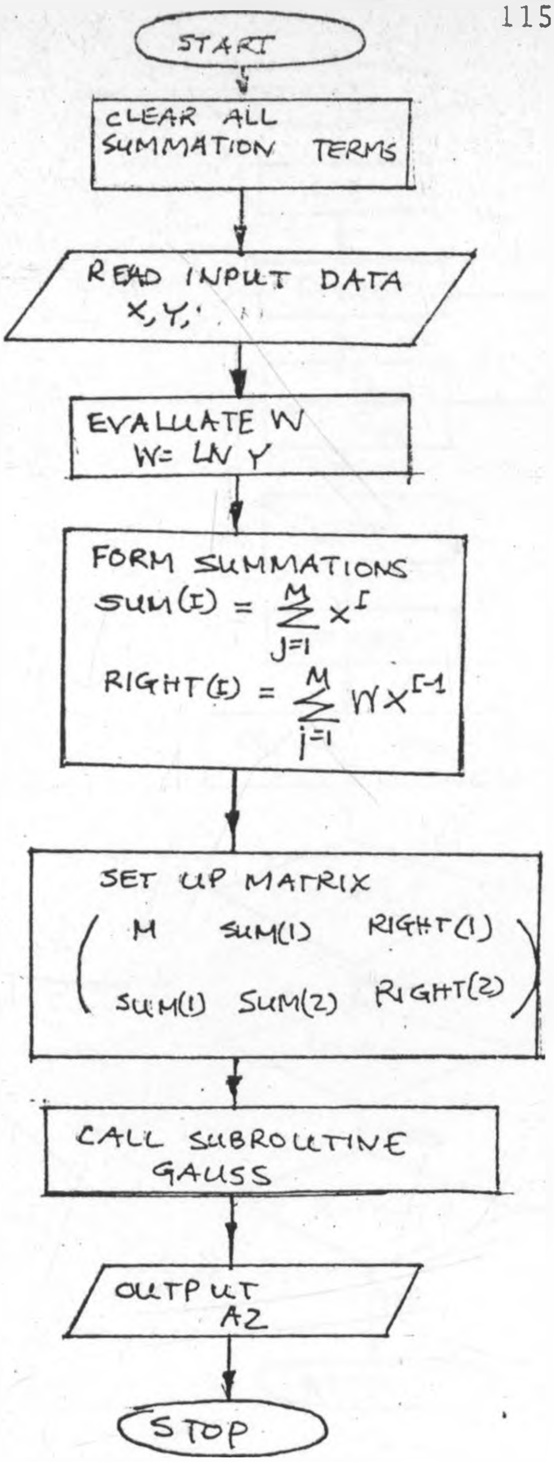


Figure 5.6: Flowchart for Programme 'Least Square Regression'

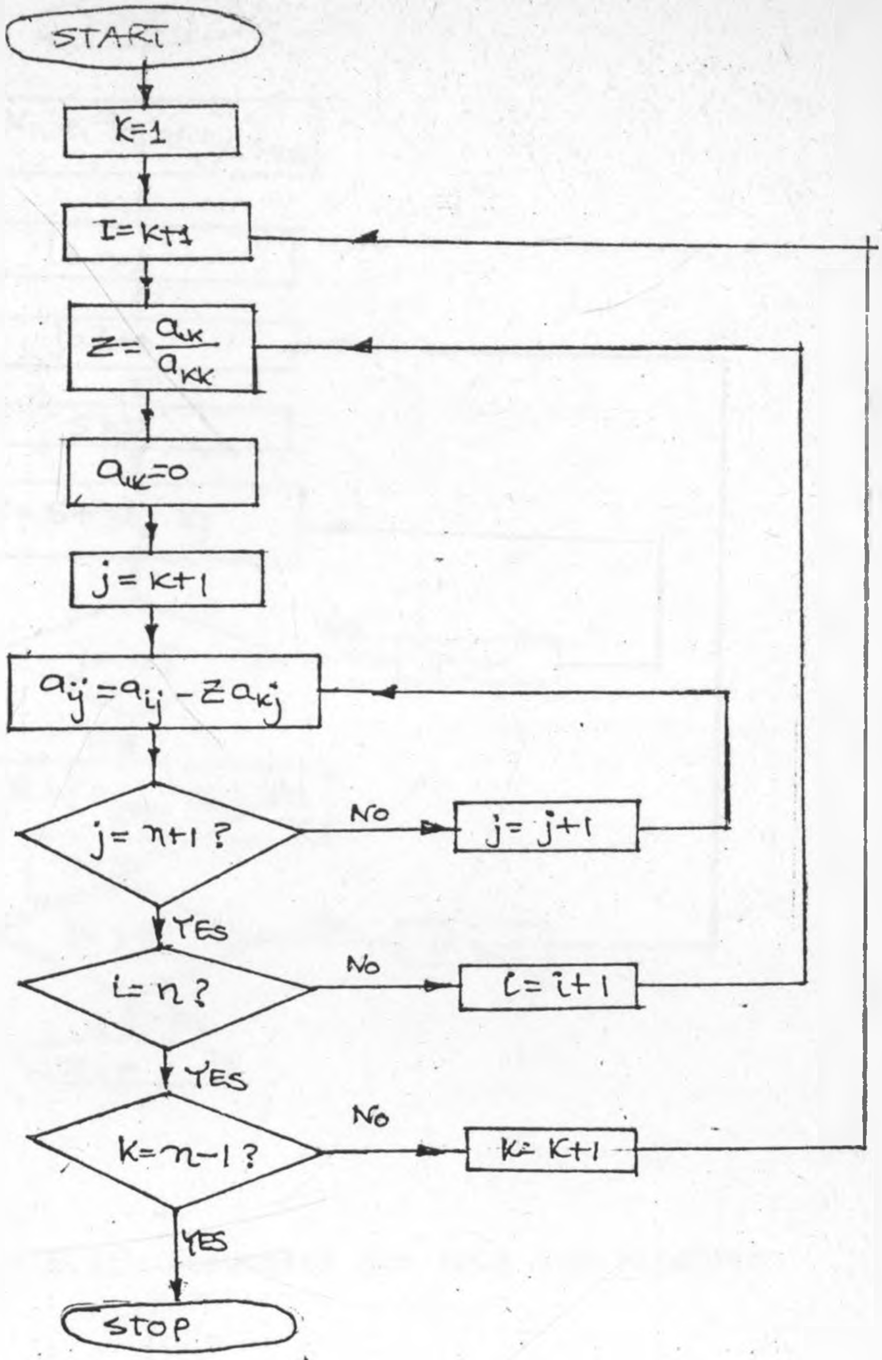


Figure 5.7: Flowchart for Subroutine Gaussian Elimination

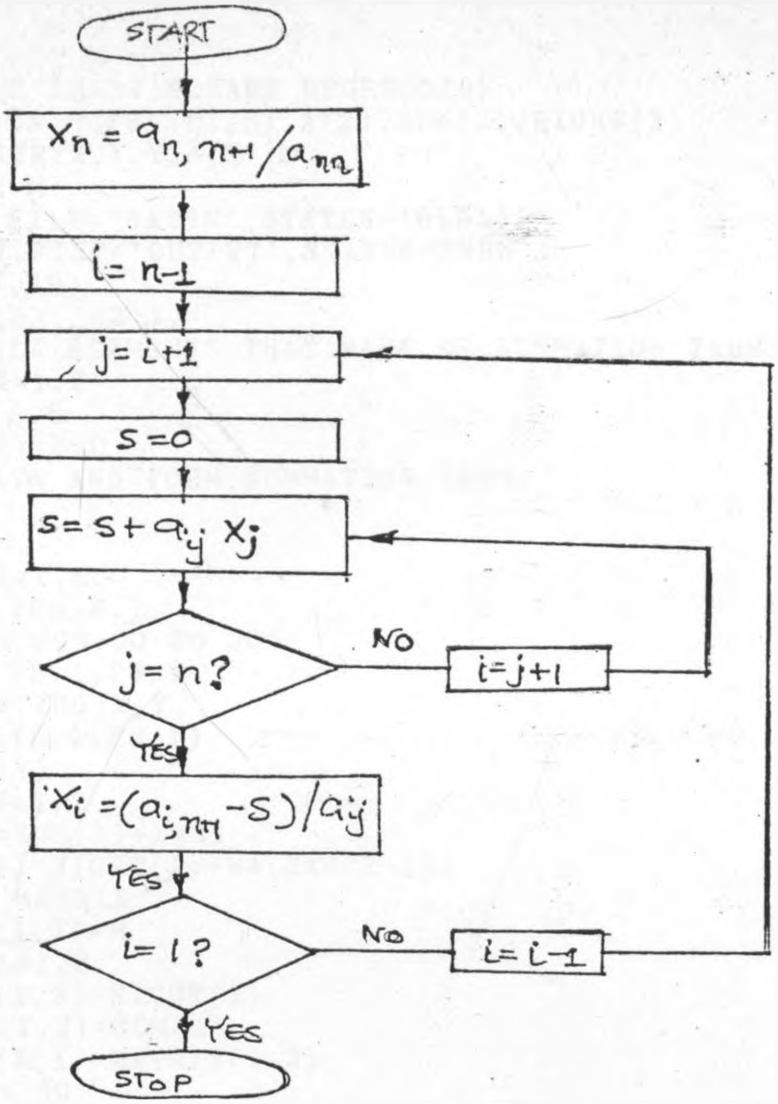


Figure 5.8: Flowchart for Back Substitution

```
C      PROGRAMME LEAST SQUARE REGRESSION
       DIMENSION MATRIX(2,3),A(2),SUM(2),RIGHT(2)
       REAL MATRIX,X,Y,A,W
       INTEGER M
       OPEN(9,FILE='DATIN',STATUS='OLD')
       OPEN (7,FILE='OUTPUT',STATUS='NEW')
       WRITE(7,10)
 10    FORMAT(5X,'A2')
 C     CLEAR ALL ELEMENTS THAT MAKE UP SUMMATION TERMS
 15    DO 30 I=1,2
 20    SUM(I)=0.0
 30    RIGHT(I)=0.0
 C     READ DATA AND FORM SUMMATION TERMS
       M=19
       N=2
       DO 50 J=1,M
       READ(9,200)X,Y,
       IF(Y.EQ.999)GO TO 350
 200   FORMAT(F5.1,F8.1)
       WRITE(*,100)X,Y
 100   FORMAT(F5.1,F8.1)
       W=ALOG(Y)
       DO 50 I=1,2
 40    SUM(I)=SUM(I)+X**I
 50    RIGHT(I)=RIGHT(I)+W*(X**(I-1))
 C     SET UP MATRIX
       MATRIX(1,1)=M
       DO 70 I=1,2
 60    MATRIX(I,3)=RIGHT(I)
 70    MATRIX(I,2)=SUM(I)
       MATRIX(2,1)=MATRIX(1,2)
       WRITE(*,80)
 80    FORMAT(2X'NOW TO SUBROUTINE')
       CALL GAUSS(MATRIX,A,N)
       WRITE(7,300)A(2)
 300   FORMAT(F7.2)
       GO TO 15
 350   CLOSE(7)
       STOP
       END
 C
 C*********************************
```

Figure 5.9: Programme Least Square Regression

```
      SUBROUTINE GAUSS(MATRIX,A,N)
      DIMENSION MATRIX(2,3),A(2)
      REAL MATRIX,A
C     ELIMINATION BEGINS HERE
      K=1
400   I=K+1
500   Z=MATRIX(I,K)/MATRIX(K,K)
      MATRIX(I,K)=0
      J=K+1
600   MATRIX(I,J)=MATRIX(I,J)-Z*MATRIX(K,J)
      IF (J.EQ.(N+1)) GO TO 700
      J=J+1
      GO TO 600
700   IF(I.EQ.N)GO TO 800
      I=I+1
      GO TO 500
800   IF(K.EQ.(N-1))GO TO 900
      K=K+1
      GO TO 400
C     BACK SUBSTITUTION BEGINS HERE
900   A(N)=MATRIX(N,N+1)/MATRIX(N,N)
      I=N-1
1000  J=I+1
      S=0
2000  S=S+MATRIX(I,J)*A(J)
      IF(J.NE.N)GO TO 3000
      A(I)=(MATRIX(I,N+1)-S)/MATRIX(I,J)
      IF(I.EQ.1)GO TO4000
      I=I-1
      GO TO 1000
3000  J=J+1
      GO TO 2000
4000  WRITE(*,5000)
5000  FORMAT(2X'BACK FROM SUBROUTINE')
      RETURN
      END
```

Figure 5.10: Subroutine Gauss

01/01/84 SYSTEM UTILITIES - FILE DISPLAY

A:/OUTPUT PAG

A2
.09 NAKURU
.14 NYERI
.12 NAIROBI (INDUSTRIAL AREA)
.10 NAIROBI (RESIDENTIAL AREA)
.08 MOMBASA
.10 KISUMU

Figure 5.11: Results

5.2.3 Results and Observations

Figure 5.11 is a printout of the contents of the ouput file OUTPUT, resulting from running the programme 'Least Squares Regression' with the input data of Tables Figure 5.1. The values of A2 resulting from the regression analysis as described in Appendix 1 are given.

The resulting growth functions of the areas are given by the following expressions, for the 19 year period considered.

(a) $N_1(t) = e^{c_1 + 0.09t}$ for Nakuru ASC area

(b) $N_2(t) = e^{c_2 + 0.14t}$ for Nyeri ASC area

(c) $N_3(t) = e^{c_3 + 0.12t}$ for Nairobi's Industrial area

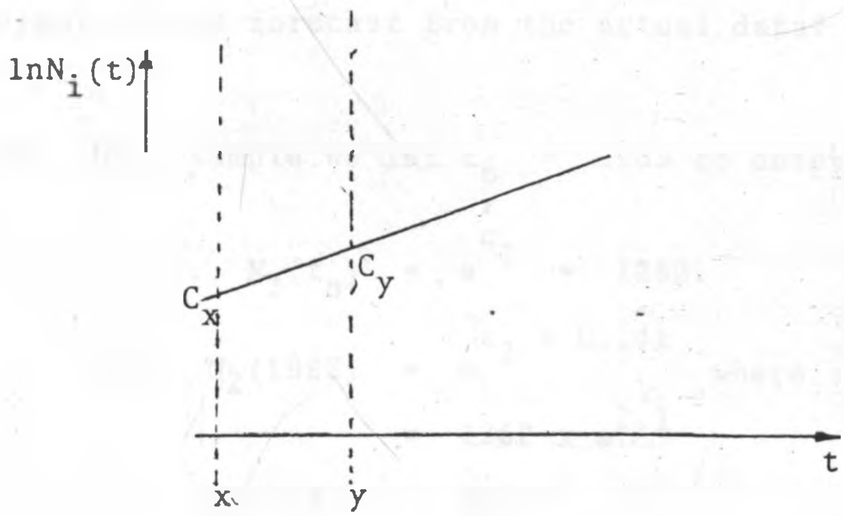
(d) $N_4(t) = e^{c_4 + 0.10t}$ for Nairobi's Residential area

(e) $N_5(t) = e^{c_5 + 0.08t}$ for Mombasa ASC area

(f) $N_6(t) = e^{c_6 + 0.10t}$ for Kisumu ASC area

(5.8)

The constants c_i vary depending on choice of the year to be considered as the base year (t_o) and does not affect the rate of growth, as illustrated in the figure below.



If t_o is chosen as x then $C_i = C_x$

If t_o is chosen as y then $C_i = C_y$

The slope of the graph is however unaltered. This illustrates the fact that the growth characteristics are fully described by the constant A2. As an investigation on whether the set of equation 5.8 represent the true growth functions the average deviation of values of $N_1(t)$ calculated from the equations from the actual data was determined. The procedure followed is best explained by way of the following example.

Consider the function 5.8b $N_2(t) = e^{c_2+0.14t}$ for Nyeri ASC area. If in 1968 equation 5.8b was used to forecast the demand of telecommunications service in 1983, what would have been the percentage error in the forecast from the actual data?

In this example we let $t_o = 1969$ to determine c_2

$$\therefore \quad N_2(t_o) = e^{c_2} = 1262.$$

$$\text{Thus} \quad N_2(1983) = e^{c_2 + 0.14t} \quad \text{where } t = 15$$

$$= 1262 \times e^{2.1}$$

$$N_2(1983) = 10306$$

But the actual $N_2(1983) = 10064$

$$\text{Thus the error} = \frac{10306 - 10064\%}{10064} = 0.02 = 2\%$$

To obtain the average percentage error for 15 year forecasts using the equation the errors for the 1968 - 1982, 1967 - 1981, 1966 - 1980, 1965 - 1979 forecast periods were calculated and their mean taken.

The table below gives the percentage errors for each area obtained as explained above, for the indicated forecast periods.

Area \ Avg.% error	5 Year Forecasts	10 Year Forecasts	15 Year Forecasts
Nakuru	8%	8%	5%
Nyeri	2%	8%	2%
Mombasa	4%	4%	6%
Kisumu	13%	12%	5%
Nairobi (I)	23%	21%	9%
Nairobi (R)	12%	7%	8%

Figure 5.12: Percentage error for various forecating periods

The table is interpreted as follows:-

Using the growth function of equation 5.7a to estimate demand at a time t years in Nakuru area for example the mean percentage error of the estimates is 8% for 5 years forecasting periods, 8% for 10 year forecasting periods and 5% for 15 year forecasting periods.

From the contents of the table highest percentage errors occur at shorter forecasting periods, with the 15 year forecasting period giving relatively lower percentage errors. For this reason the 15 year forecasting period is considered optimum in the present exercise, giving errors ranging between 2% and 9%.

It is further observed from the table that larger errors are obtained from the Nairobi areas (both residential and industrial). The conclusion to be drawn here is that there are factors that affect telecommunications demand in a manner that cannot be accommodated simply in the trend curves. This behaviour is expected when observing the graphs for the Nairobi area cases. It would therefore be erroneous to forecast demand in these areas by considering historical data alone.

For the remaining areas it is safe to say that the demand growth is well approximated by the growth functions of equation 5.8 . Indeed since forecasts are estimates, error margins of 2% to 6% in a period of 15 years can be considered acceptable.

5.3 FORECASTING OF DEMAND FOR TELECOMMUNICATIONS SERVICES

5.3.1 Forecasting Methods

There are many methods of forecasting the future development of telephone services in a country, the principal ones being:-

(a) Intuitive forecasting - which is a systematic assessment based on subscriber surveys. These surveys are developed to produce forecasts of future demands.

(b) Normative forecasting - where it is assumed that there will exist some needs in the future which will affect the demand for telecommunications services.

(c) Comparison methods - where the demand and growth characteristics of a particular area are forecasted on the basis of known historical patterns of another area.

(d) Trend methods - which depend on the existence of a sound data base of past statistics. Past trends are analysed from this data and used to forecast future growth. The assumption here is that future trends will have a predictable relationship with past trends.

5.3.1.1. Trend Methods

In this work trend methods will be used for the areas with adequate data with the aim of getting as realistic a picture as possible of the future demand for telephones. One simple approach is to calculate the future number of telephone instruments on the assumption that the annual percentage growth of telephones will be roughly the same in the future as in the past. This method has been used in the developed countries since World War I[3]. The development of the telephone density in 15 countries is shown in Figure 5.13 from which it is apparent that this method could be applicable for short term prognosis (5 - 15 years) for those Western European countries which in 1925 had a density exceeding 1.5 per 100 inhabitants.

As previously discussed, the approximately straight line plots of Figure 5.2 for Nakuru, Kisumu, Nyeri and Mombasa leads to a conclusion that a fairly constant rate of growth has been experienced in the previous (19 year) period. An extrapolation of these straight line graphs would extend this bahaviour to future years. Looking at graphs Figure 5.4 reveals that no saturation is expected within the next say 10 - 15 years even if

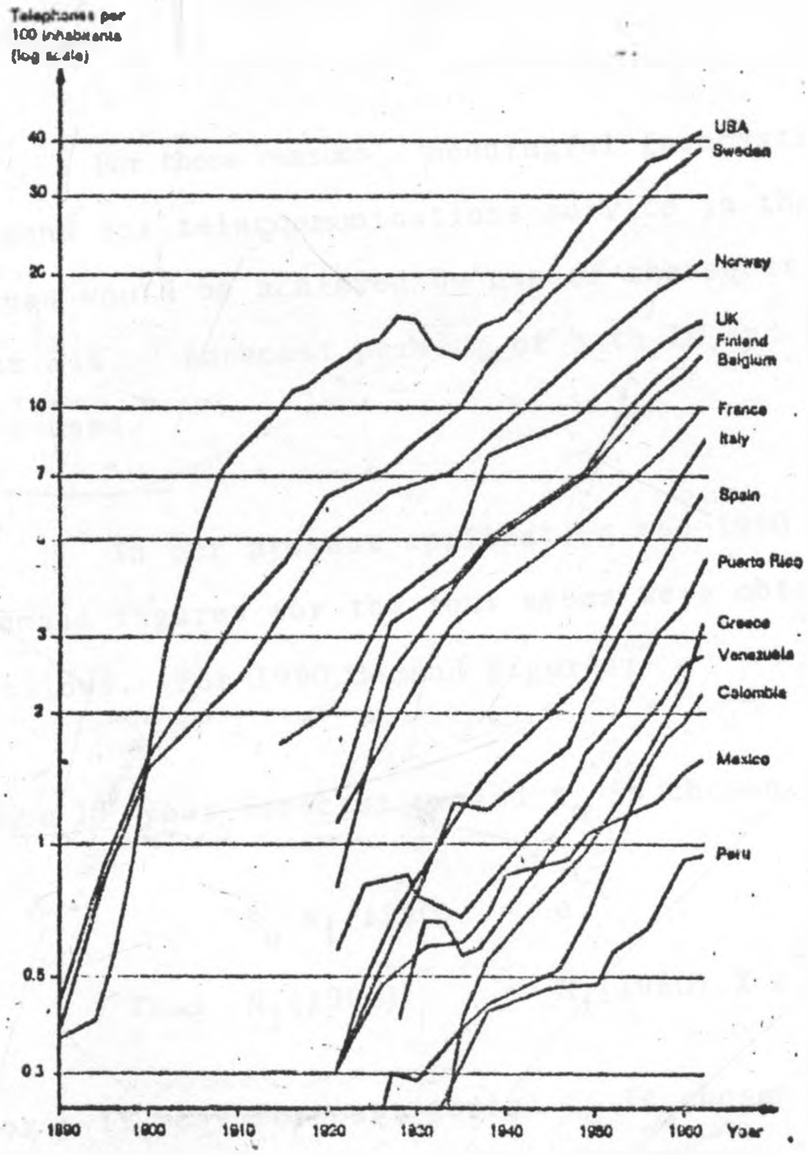


Figure 5.13: Telephone Density in 15 Countries[3]

all demand for service was to be satisfied. Another factor to be considered is that the telephone penetration in the Kenyan network is still very low, which further confirms that saturation is not eminent.

For these reasons meaningful forecasts of demand for telecommunications service in the four areas would be achieved by use of the equation set 5.8 . Forecast periods of both 10 and 15 years are used.

In our present application the 1990 and 1995 demand figures for the four areas were obtained as follows. For 1990 demand figures:-

For a 10 year forecast period t_o is chosen as 1980

$$S_o\ N_i(1980) = e^{C_i}$$

$$\text{Thus}\quad N_i(1990) = N_i(1980) \times e^{10a_2}$$

For a 15 year forecast period t_o is chosen as 1975

$$N_i(1975) = e^{C_i}$$

$$\therefore\ N_i(1990) = N_i(1975) \times e^{15a_2}$$

Similarly the 1995 demand figures $t_o = 1980$

and $N_i(1995) = N_i(1980) \times e^{15a_2}$

The table below gives these forecasted demand figures.

Area \ Demand	10 years 1990	15 years 1990	1995
Nakuru	9795	10217	15371
Kisumu	9490	11446	15631
Nyeri	26971	25433	54273
Mombasa	34962	33227	52051

5.3.1.2 Comparison Method

This prognostic method implies that the number of telephones in an area A is based on a comparison with the historical trend of a more developed area B.

If for example the telephone density in area A is the same as it was in Area B x years ago, and the general telephone development is assumed to follow the same trend in the two areas, a prognosis can be made for the total number of telephones during the next x year period of area A, provided that reliable forecasts of the future growth of population are available. This method of forecast has been applied[4] to the telephone density forecasts of France as compared to Sweden.

Figure 5.14 gives the telephone density development in France and Sweden. France had the same telephone density in 1962 as Sweden had in 1934. If the telephone density in France in the future follows the same development trend as it did in Sweden between 1934 and 1962, France is expected in 1990 to reach the Swedish telephone density standard of 1962.

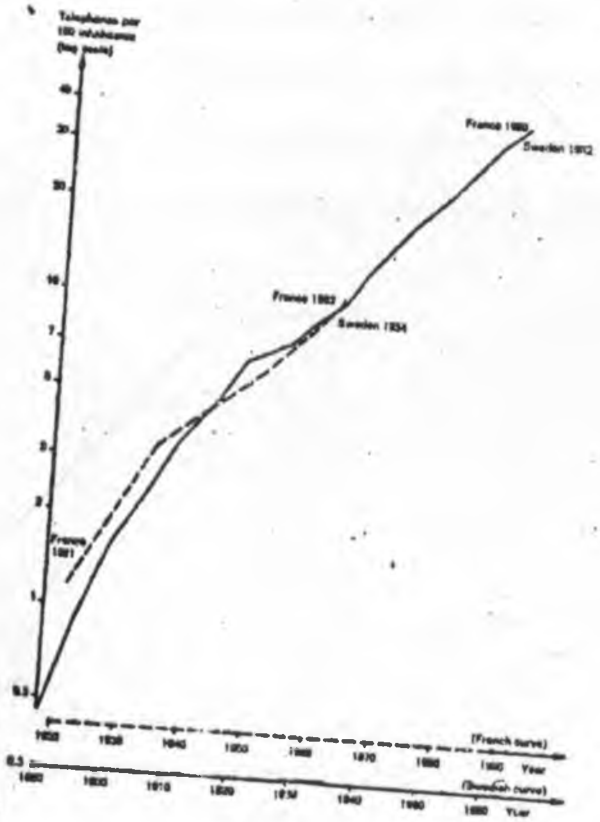


Figure 5.14: Comparison Method[4]: Telephone density in Sweden 1890 - 1962 and in France 1921 - 1962

The disadvantage of this method when applied to two countries is that there are hardly any two countries which follow parallel development . In cases where two regions in the same country are considered it can be useful. In the present case the rate of growth in the five areas has been approximated to range from A2 = 0.08 to A2 = 0.14. Thus for a town area like Kericho for example for forecasting purposes a growth rate in this range could be used with little error anticipated.

CHAPTER SIX

CONCLUDING COMMENTS

It has been established that approximately 24% of links connecting automatic exchanges are congested. Teletraffic experiences significant blocking on these routes resulting in users' complaints. However it is also observed that there are some routes where the circuit provision is far in excess of the requirements for the offered traffic. This is particularly so in the Coast Network where a route such as the Nairobi NSC - Mombasa GSC carries 79.3 erlangs on 140 circuits. The Mombasa GSC - Malindi route carries 7.0 erlangs on 29 circuits, while the Malindi - Mombasa GSC route carries 7.4 erlangs on 29 circuits. Noting that the coast network has two congested routes it is possible that this congestion can be alleviated by redistribution of equipment from over provided to congested routes. In doing this care should be taken to identify the available transmission system to accompany the available switching plant at both exchanges. Also the signalling system employed on the over provided route must be the same as that employed on the congested route.

A similar treatment is extendable to other networks, and therefore to the Kenyan Telecommunications network as a whole. Whereas it is not always possible to increase telecommunications plant due to economic constraints, it is noted that by proper utilization and distribution of available plant congestion can be alleviated on some routes. By standardizing in future on Multi-Frequency Compelled Signalling (MFC) more equipment on different routes will be interchangeable thus allowing for easy redistribution of equipment.

The demand for telecommunications services has not been successfully met by the Kenyan network. In some areas this is due to lack of sufficient switching equipment, while in other areas it is due to insufficient distribution line plant. By considering the effective capacity of switching equipment in an area, a conclusion is drawn as to the reason for not satisfying demand.

A tabulation of effective capacity against demand for the years 1975, 1980 and 1985 in Mombasa, Nakuru, Nairobi and Kisumu is shown overleaf.

MOMBASA	Effective Capacity	Demand
1975	12,684	10.008
1980	13,388	15,678
1983	20,790	19,431
NAKURU		
1975	2,080	2,547
1980	3,322	3,982
1983	5,702	6,438
NAIROBI (RESIDENTIAL)		
1975	3,000	3,764
1980	5,200	5,083
1983	7,000	8,166
NAIROBI (INDUSTRIAL)		
1975	5,000	6,490
1980	6,000	9,363
1983	11,000	13,221
KISUMU		
1975	2,460	2,555
1980	4,890	3,489
1985	6,640	4,754

In the Nairobi areas and Nakuru, unsatisfied demand is mainly due to insufficient switching equipment, whereas in Kisumu and Mombasa the demand results from inadequate distribution line plant.

Systematic and reliable demand forecasting minimises inadequate provision of telecommunication plant while ensuring that unnecessary plant is not installed. One such method giving realisting forecasts has been presented in this thesis. Although the method does not address itself to unforeseen circumstances such as sudden mushrooming of settlements brought about by newly constructed estates, affordability in the event of reduction of fees and increased demand due to better service availability among others, these can be taken care of by allowing a reasonable margin in the forecasts. These margins are dependent on the area, but bigger margins (10% - 15%) should be used in highly industrial areas.

Further studies in this field should include finding the relationship between the growth of demand for telephones and income per capita, as well as the relationship to population growth. Empirical research shows that a simple relationship exists between these parameters. Since a large number of economists today are engaged on studies of growth of national incomes it is possible to obtain relatively realistic figures about economic development decades ahead. This, in addition to the methods in this thesis would enable even more reliable forecasts on telephone demand provided that a realistic formula has been obtained for the relation between national income per capita and telephone demand growth. The forecasting period would also be increased.

In the present set up the traffic department is involved in collecting data and processing it by use of traffic tables. This method is tedious and time consuming involving many personnel. By adopting the methods presented in this thesis more time can be devoted by the personnel to the continuous observation of teletraffic thus improving the reliability of the data. The Data Processing Department can then run the computer programmes on the main ICL computer situated at the Kenya Post and Telecommunications Corporation (KP & TC) headquarters building. As the KP & TC network is approaching a transitional stage towards digitization, it is an appropriate time to ensure that the shortcomings of the existing analogue network are remedied. Digital Switching systems are to be introduced in both urban and rural areas, and sufficient telecommunications plant should be catered for. It is hoped that the findings and methods in this thesis will be adopted to achieve this.

Appendix I

METHOD OF LEAST SQUARES

1.1 Best possible fit principle

This is a method that is defined as a method of compromising.

Consider a set of three measurements of an unknown parameter u:-

Measurement	Result
1	u = a
2	u = b
3	u = c

Generally $a \neq b \neq c$. The problem at hand is that of finding the true value of the unknown parameter u. This problem requires solving three equations with only one unknown variable u. Although this is impossible a best possible fit may be found by calculating the value of u which minimises the sum of the squared errors in the results.

The function of u to be minimised is:-

$$F(u) = (u - a)^2 + (u - b)^2 + (u - c)^2$$

The derivative

$$\frac{dF(u)}{du} = 2(u - a) + 2(u - b) + 2(u - c)$$

For a minimum

$$\frac{dF(u)}{du} = 0 = 2(u - a) + 2(u - b) + 2(u - c)$$

$$u = \frac{a + b + c}{3}$$

Thus the arithmetic mean of the measurements is the best possible fit in the meaning of method of least squares.

1.2 Normal Equations

Consider now a case where the number of equations is greater than the number of unknown variables.

$$a_{11}u_1 + a_{12}u_2 = c_1$$

$$a_{21}u_1 + a_{22}u_2 = c_2$$

$$a_{31}u_1 + a_{32}u_2 = c_3$$

To obtain a compromising solution the function which is the sum of the squared measurement errors is minimised. That is:-

$$F(u_1u_2) = (a_{11}u_1 + a_{12}u_2 - c_1)^2 + (a_{21}u_1 + a_{22}u_2 - c_2)^2 + (a_{31}u_1 + a_{32}u_2 - c_3)^2$$

is to be minimised.

But

$$\frac{dF(u_1u_2)}{du_1} = 2(a_{11}u_1 + a_{12}u_2 - c_1)a_{11} + 2(a_{21}u_1 + a_{22}u_2 - c_2)a_{21} + 2(a_{31}u_1 + a_{32}u_2 - c_3)a_{31}$$

$$\frac{dF(u_1u_2)}{du_1} = 0 \qquad a_{11}^2u_1 + a_{11}a_{12}u_2 - a_{11}c_1 + a_{21}^2u_1 + a_{21}a_{22}u_2 - a_{21}c_2 + a_{31}^2u_1 + a_{31}a_{32}u_2 - a_{31}c_3 = 0$$

or $$(a_{11}^2 + a_{21}^2 + a_{31}^2)u_1 + (a_{11}a_{12} + a_{21}a_{22} + a_{31}a_{32})u_2 = a_{11}c_1 + a_{21}c_2 + a_{31}c_3$$

Similarly from

$$\frac{dF(u_1u_2)}{du_2} = 0 \quad \text{we get}$$

$$u_1(a_{12}a_{11} + a_{22}a_{21} + a_{32}a_{31}) + u_2(a_{12}^2 + a_{22}^2$$
$$+ a_{32}^2) = a_{12}c_1 + a_{22}c_2 + a_{32}c_3$$

By solving these equations for u_1 and u_2 the best compromise solution is found.

In our application there are 19 plottable points for each station $(w_{11}x_1)$, $(w_{21}x_2)$ ... $(w_{19}x_{19})$. The solution for the problem consists of determining the unknown parameters a_1 and a_2 so that the straight line $w = a_1 + a_2x$ reproduces the 19 plotted points as well as possible.

In order to fit the straight line to the 19 plotted points it is considered that everyone of the points satisfies the equation of the straight line. Thus the system equations are:-

$$\begin{aligned} w_1 &= a_1 + a_2x_1 \\ w_2 &= a_1 + a_2x_2 \\ w_3 &= a_1 + a_2x_4 \\ &\vdots \\ w_{19} &= a_1 + a_2x_{19} \end{aligned} \qquad \ldots\ldots 1$$

This is a set of 19 equations with only two unknowns; a_1 and a_2. In matrix form the system is:-

$$\begin{bmatrix} 1 & x_1 \\ 1 & x_2 \\ 1 & x_3 \\ 1 & x_4 \\ , & , \\ , & , \\ , & , \\ 1 & x_{19} \end{bmatrix} x \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \\ , \\ , \\ , \\ w_{19} \end{bmatrix} \qquad \ldots\ldots 2$$

By denoting

$$A = \begin{bmatrix} 1 & x_1 \\ 1 & x_2 \\ , & , \\ , & , \\ 1 & x_{19} \end{bmatrix} ; \quad u = \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \quad \text{and } c = \begin{bmatrix} w_1 \\ w_2 \\ , \\ , \\ w_{19} \end{bmatrix}$$

The system equation in matrix form becomes

$$A \cdot u = c$$

Note that $A_1 = \begin{bmatrix} 1 \\ 1 \\ \vdots \\ \vdots \\ 1 \end{bmatrix}$ and $A_2 = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ \vdots \\ x_{19} \end{bmatrix}$

The normal equations for this problem are then

$$a_1(A_1'A_1) + a_2(A_1'A_2) = (A_1'c)$$
$$a_1(A_2'A_1) + a_2(A_2'A_2) = (A_2'c)$$

This is

$$\begin{bmatrix} 19 & \sum_{i=1}^{19} x_i \\ \sum_{i=1}^{19} x_i & \sum_{i=1}^{19} x_i^2 \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{19} w_i \\ \sum_{i=1}^{19} x_i w_i \end{bmatrix} \quad \ldots\ldots 3$$

The solution for $\begin{matrix} a_1 \\ a_2 \end{matrix}$ is obtained by employing simplified gaussian elimination on the matrix

$$\begin{bmatrix} 19 & \sum_{i=1}^{19} x_i & \sum_{i=1}^{19} w_i \\ \sum_{i=1}^{19} x_i & \sum_{i=1}^{19} x_i^2 & \sum_{i=1}^{19} x_i w_i \end{bmatrix} \quad \ldots\ldots 4$$

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