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A ROAD INVESTMENT MODEL FOR THE SUDAN

A Dissertation

Presented for the

Doctor of Philosophy

Degree

The University of Tennessee, Knoxville

Gaafar Hassan Elshaygi

June 1983

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DEDICATION

In the Name of ALLAH, The Beneficent, The Merciful

This work is dedicated:

To my wife and our beloved daughters, Maisoon and Samah, whose patience and concerns and the sacrifices they made in companionship to stand by me in the affliction and tribulations of this research and my entire graduate work in the United States, have made the whole undertaking worthwhile.

To my parents in recognition of the unlimited favors they bestowed upon me and their constant love and prayers with which I have been touched and inspired throughout my life.

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ABSTRACT

Efficiency has become a critical factor in overall development of the Sudanese road system because of increasing demand for transportation, spatially separated supply and demand points, and a low level of service offered by the road network. In this study, an investment programming model is developed and applied to the interregional road transportation system in the Sudan to determine improvements which maximize the network efficiency as measured by the minimization of ton-kilometers weighted by relative travel time. The improvements of road surfaces from earth to gravel, gravel to pavement, and earth to pavement satisfy specified budget and demand requirements over a short planning horizon.

A heuristic procedure which involves solving an alternative series of shortest path and optimization problems is employed to solve the model for various budget levels. The result is a number of alternative investment program sets each of which results in substantial reduction of the total sum of weighted ton-kilometers used by the system. Based on a cost-effectiveness measure, the best investment program set is identified for possible implementation.

The degree to which the model results deviate from optimality is evaluated by comparing the heuristic solutions to the lower bounds generated by reformulating an equivalent integer model and solving it by linear programming. The results of the original model are found to deviate no more than 7-5% from optimality.

In its application to the Sudanese situation, the model is capable of handling aspects of project planning that have not been treated in this way before. Chief among these aspects are the spatial distribution of investment projects, their priority ranking, and measures of network efficiency improvements. It is suggested that the model could also be used to determine optimal vehicle fleet requirements. The model handles the problem of partial link improvements effectively and allows for link improvements to be made in a continuous rather than a discrete fashion.

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CHAPTER I

INTRODUCTION

The study of spatial arrangement (structure, pattern, or location) and its determinants using mathematical optimization methods is a relatively recent development in the field of geography. The spatial allocation of resource investment and corresponding changes in the configuration of transportation networks are often products of conscious decisions which may have been facilitated by the utilization of optimization techniques. Generally, two classes of research on optimization which are of concern to transportation geographers can be identified: transportation network analysis and network synthesis. In transport network analysis a specified network configuration is analyzed to predict how a particular set of traffic demands will utilize the network; or the network is analyzed to find the optimal flow pattern with respect to some objective function. In network synthesis problems one seeks an optimal network configuration which satisfies a given set of requirements. These requirements may be met, for example, by changing the capacity of parts of the network so as to improve the level of service provided. Such changes are usually made by upgrading capacity of network links. For most applications, the problem of interest is expansion of the network through investment in upgrading (or rehabilitating) existing facilities or building new ones.

The solutions to models that are based on network synthesis may provide the geographer with the spatial configuration of a new

transportation system. The practical value of such synthesis models is especially evident in the case of developing countries. The spatial configurations of transport networks are important determinants of interregional comparative advantages (38). Changes in network structure often affect regional economic and population growth patterns. It is thus important to formulate strategies which allow the geographer to generate networks which optimize the attainment of a goal or goals subject to some constraints that recognize the interrelated nature of transportation improvements and the socioeconomic consequences touched off by such improvements (47). The scope of this research concerns the transportation network synthesis and development of a strategy for road improvement in the Sudan through investment programming.

Introduction to the Problem

The purpose of transportation investment is to facilitate the movement of increasing numbers of people and/or volumes of goods. In developing countries generally and in the Sudan in particular, the relationship between productive economic activities and transportation capacity has become critically important (72). The Sudan is a relatively large country with a low density of population, where agricultural and industrial production has expanded continuously since 1960. Specialization and diversification in agricultural and industrial production has occurred, the rate of urbanization and labor mobility has increased, and local processing of raw materials is receiving increasing attention. The nature of freight and passenger transport demand has,

therefore, become more complex. The existing transportation system in the country has been unable to keep pace with the demands of such a rapidly growing economy. The Sudanese government has recognized that transportation facilities for passenger and freight movement are inadequate and is undertaking a large transportation investment program. This investment is aimed not only at increasing the capacity and efficiency of railways, but also in developing an expanding alternative transportation system. In particular, emphasis is on road development (73). Of the total investment funds of L$500 million* envisaged for the transportation and communications sector program during the Six-Year National Development Plan 1977-1983, 50% was allocated to the improvement and expansion of road transportation facilities. Because roads are likely to be much more important than other modes of transportation in the country, this research will focus solely upon road improvement.

Capital in the Sudan is scarce and the demands on developmental funds are heavy. The unit cost of investment in road transportation is relatively high to begin with because of low population density and low transport volume per unit area. Without large scale investment in road transportation facilities, however, the returns from other production-oriented investments will be low. These factors make it all the more important that an efficient road transportation system be developed. Specifically, there is a need to achieve a balance between maintaining

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*One Sudanese pound equalled 2.853 American dollars in 1975; since then, the Sudanese pound has been devalued twice; it is now worth about 50% of its 1975 value.

the maximum possible efficiency level in the road system at the lowest cost. The critical decision to upgrade (or build) or not upgrade some particular road transport link depends upon an accurate evaluation of different alternatives among road improvement possibilities. These link improvement decisions must be made in light of the overall road transportation system which will provide the country the greatest benefit, i.e., maximum transportation improvement per amount of development capital invested.

Objectives of This Study

This study is intended to provide some insights related to road transportation and its improvement in the Sudan. It is concerned with spatial efficiency of an improved interregional road network system and how that network could be obtained using optimization methods. The improved network and its efficiency will be generated by simulating investments in upgrading the existing interregional roads. A model (program) for investment planning is developed and will be applied to the Sudanese road network system to determine the optimum improvements which maximize the level of efficiency in the network and therefore improve overall level of service offered by the road system, given a budget and demand constraints. The optimization technique will aid in evaluating road link alternatives which would be considered for investment in any link type combination. Alternatives consist of the following possibilities: upgrading a road link or portion of it from earth to gravel, gravel to pavement, or earth to pavement. Utilization

of optimization techniques will, therefore, aid in generating decisions about investment and concurrent changes which would determine the spatial efficiency of the road system and the network configuration.

In accordance with the basic purposes of this study, a set of research questions is posed. These questions form the basis for the formulation of the investment program considered in this study and their answers form the basis of the study's results. The questions are:

1. What are the basic structural and network characteristics and the pattern of flows on the road system in the Sudan? How do these characteristics serve as constraints for overall road network development in the country?
2. Given alternative combinations of road lengths differentiated by road type, and associated levels of service measured in terms such as average speed or cost of travel, what and where should changes in the network be made?
3. What is the magnitude of investment required so that overall road system efficiency meets anticipated economic growth (i.e., where are these upgraded links located; how much road should be upgraded from one level to another, and how much money should be allocated for the improvement)?
4. What are the economic, social, political, and policy implications of the improved road system obtained for the overall development of the country?

The model consists of an objective function and a set of constraints. The objective function is to minimize total weighted ton-

kilometers (on the basis of relative travel time) in the road system so that overall network efficiency is maximized. On the basis of this optimization criterion, investment decisions are taken to be the number of kilometers a particular road link or link segment is to be upgraded from earth to gravel, gravel to pavement or earth to pavement. The service improvements as measured by upgrading the type of road are programmed to the existing road system so as to obtain overall efficiency of the road transport system as measured by minimizing total weighted ton-kilometers on the basis of relative average travel time. The results of the program are an improved network structure, costs of investments, and a new level of network efficiency. By evaluating these results in terms of the questions posited, the objectives of this study will be accomplished.

The Setting of the Study Area

The Sudan is situated in northeast Africa, between latitudes 22°N and 4°N. The maximum distance from north to south is about 2,040 km. and from east to west is 1,600 km. The Sudan is the largest country in Africa, with an area of about 2.6 million square kilometers which forms 8.3% of the area of the continent. The country was divided into ten provinces: Red Sea, Kassala, Northern, Khartoum, Blue Nile, Darfur, Kordofan, Upper Nile, Bahr El Ghazal, and Equatoria; but in 1974 the provinces were redefined and now number sixteen. The country's Red Sea coastline is about 640 km. long. The Sudan is bordered on the north by Egypt, on the east by the Red Sea and Ethiopia, on the south by Kenya,

Uganda, and Zaire, on the west by the Central African Republic and Chad, and on the northwest by Libya.

Virtually the entire country is a plain (1,500 feet in elevation) with some isolated mountainous areas such as the Red Sea Mountains along the coast, the Nuba Mountains in Kordofan, and Jebel Marra Mountain in Darfur, and the plateaus at the northeastern border of the southern part of the country (comprised of Upper Nile, Bahr El Ghazal, and Equatoria provinces). The Blue Nile and White Nile and their tributaries are the most prominent physiographic features in the country. Other rivers flow toward the White Nile in the south but disappear into the Sudd, the largest swamp in the world. A network of small tributaries (wadis) flow towards the river in the central Sudan Nile basin.

Located entirely within the tropics, the Sudan has a tropical continental climate with hot wet summers and dry cool winters, a characteristic of the savannah. In the northern third of the country between latitudes 22-16° (the Northern Province, northern parts of Kordofan, Darfur, and Kassala Provinces), rainfall is less than 2" and true desert exists. Soils are sandy and vegetation does not exist except along wadi basins and the Nile. True desert merges into semi-desert acacia scrub between latitudes 16-17°, with a total annual rainfall of 2-6". In the central third of the country between latitudes 10-16° (Darfur, Kordofan, Blue Nile, and Kassala) total annual rainfall varies from 6-30". In most parts of the area vegetation (which is short grass and low wood savannah) has been cleared for cultivation. In the southern third, south of latitude 10° (southern three provinces), total

annual rainfall ranges between 30-80". Soils are laterite, and trees, including evergreen, are the dominant form of vegetation.

On the whole the topography of the Sudan does not provide a major obstacle in the construction of road transportation facilities. Rainfall and soils are in some cases considered a handicap for road transportation and have direct effects on the spatial distribution and patterns of road density and volume of traffic. It should be noted, however, that some climatic advantages are often overlooked. The long dry season, especially in northern Sudan, makes the transport on earth tracks feasible for the greater part of the year.

The Sudan had a population of about 18 million and a per capita income of about $450 in 1980 (122). The country has a vast agricultural and pastural potential that has been only partially exploited. More than 84 million hectares (ha.) of arable land is estimated to be available in the country (88). The Blue and White Nile rivers provide water for the largest irrigation system in tropical Africa, although it has utilized only about half of the Nile waters allocated to it under the Nile Waters Agreement with Egypt. Agriculture provides occupation for 80% of the population and accounts for 40% of the gross domestic product (GDP). Agriculture is also the source of virtually all exports, and it provides raw materials for much of the country's industrial activity. Cotton, groundnuts, sesame, and gum-arabic are the major cash crops whereas sorghum, millet, wheat, rice, maize, and cassava, in order of importance, are the major food crops. Livestock numbered about

49 million head in 1979, mainly cattle, sheep, goat, and camels, in order of herd size. The raising of livestock provide a living for 40% of the people in the Sudan.

The industrial sector contributed about 9.4% of total GDP in 1977/78, representing the second largest number of workers (12.6% of total labor force). Modern manufacturing industries have geared their activities to the utilization of the country's primary resources; namely agricultural food, dairy, sugar, edible oil, and textile industries. Other major industries are tanneries, cement production, beverage production, kenaf (sacks), and tobacco industries.

Other economic activities in the Sudan are forestry and fisheries. Forests cover more than one-fifth of the country's area, providing commercial products such as gum-arabic and timber. Freshwater resources for fisheries cover about 2 million ha. but many of these waters are inaccessible.

Mining in the Sudan accounts for a small proportion of the GDP at present, but the production of minerals is increasing. Chromite is one of the most important minerals in the country. Other mineral deposits include iron-ore, gypsum, manganese, mica, asbestos, lead, and zinc. Whereas some of these mineral resources have been exploited, others are considered for exploitation. Recent discoveries of oil in the interior may allow the Sudan to become self-sufficient. Explorations are continuing with encouraging primary results.

Sudan Road Transportation as an Area of Study

It can be seen from the above discussion that there are a number of reasons which make the road transportation system in the Sudan an interesting area of study. The geographic diversity of the Sudan offers potential for development in numerous areas, but the enormous size of the country poses great problems for the construction of a road transportation network because of the capital investment required. A growing trend toward a spatially specialized economy has clear consequences for the transportation sector in the Sudan. Distances between production and consumption or export centers are large, and an efficient marketing system depends largely on the performance of the transportation system. As transport efficiency improves, the goods produced in an area become more accessible to external markets (6). In developing countries that depend heavily upon agriculture, as the Sudan does, road transportation as a general rule offers the best possibility for stimulating economic development (16). The technological, economic, and financial pay-off from road transport is better than that from other modes (2). The development of an efficient road system through investment to upgrade the types of roads in the Sudan, which is the present study's intent, will improve the level of service by providing greater accessibility between regions of production and consumption. The investment program developed in this study will, it is hoped, assist the Sudanese people in responding to social and economic changes in their country, and to manage their scarce resources in an efficient way. It will also be

helpful to geographers in providing a better understanding of the relationship between the location and magnitude of road investment decisions in the Sudan in particular and in developing countries in general.

Organization of the Study

The study is presented in two major parts. The first part contains five chapters. In this chapter, the introduction to this study has been presented and the purpose of the research is stated.

In Chapter II, various approaches used in formulating the road investment problem in developed and developing countries have been drawn together and compared as to objective function, constraints and assumptions. While the use of many of these approaches in designing road improvements in the Sudan is, in many ways, shown to be unsatisfactory for practical as well as theoretical reasons given conditions characteristic of the Sudan, the most suitable objective, constraints and assumptions on the basis of which the present formulation is based are stated in this chapter.

In Chapter III, the spatial distribution of existing and potential social and economic activities is analyzed in terms of population, agriculture, industry, and other productive factors. The purpose of this examination is to explain existing regional disparities of these activities and identify the regions accordingly as areas of supply or demand areas. These activities represent the road transport generating sources on the basis of which regional traffic volumes are determined;

their analysis, therefore, would reveal the degree of variation in level of traffic volume among the ten regions considered in the study.

Chapter IV deals with existing volume, structure, and pattern and directions of commodity and passenger flow, from producer regions to centers of consumption or destination over the existing system of Sudanese roads. The variations in the growth of network from region to region are also described in this chapter.

Chapter V represents an analysis of the road transportation supply system as measured by network growth and spatial pattern and road characteristics which affect the general performance and level of service provided by the road system.

This first part of the study addresses the research questions: What are the basic structural and network characteristics and the pattern of flows on the road system in the Sudan? How do these characteristics serve as constraints for overall road network development in the country? This part is important for the study on two counts. First, it gives the background to the information and data used to calibrate the model and gives insight into the nature of these data. Second, it is important for distinguishing the relationships between existing and potential traffic demand on one hand, and existing road transportation supply and the interregional road transportation requirements on the other hand. The first part of the study, therefore, contributes a better understanding of the interregional road transportation investment problem analyzed in the second part of the study.

The second part, the theoretical setting, addresses the remaining three sets of research questions posed in the study (see page 5) and

represents the analytical core of this study. This part contains five chapters (VI-X) of which Chapter VI is devoted to the formulation of the model. This involves the theoretical and structural setting of the model which, given certain data about potential regional traffic demand, some measures of road links performance, investment costs, and a set of constraints, attempts to determine improvements in the road links which minimize total weighted ton-kilometers so that the road network efficiency is maximized.

Chapter VII consists of three sections. The first section focuses on the calibration of the model and involves discussion of data needed for the calibration. The distribution of freight traffic (i.e., demand between all pairs of nodes in the network) is known and fixed for 1985. Their source, reliability, and limitations of these data are discussed. Also the way in which traffic flows are manipulated and prepared to fit the model design is explained. This is followed by a description of the existing interregional road system defined for the study in terms of link type and length. The graphical representation and corresponding actual spatial connections of the network are also described and mapped. Also discussed in this section are budget levels available during the planning period for making improvements, weights associated with each road type, investment costs, and road standards for which road links are to be upgraded. The bases on which these inputs to the model are determined and limitations of data on improvement costs are noted. The second section of Chapter VII contains a brief description of the method developed to solve the model. This is a heuristic procedure which

involves a cyclic operation whereby a series of shortest path and optimization problems are solved alternatively. The steps involved in the procedure to solve the model are illustrated theoretically and schematically. In the final section practical application of the cyclic heuristic procedure to solve the model is shown, computer outputs are interpreted, and results of all solutions obtained are displayed in Appendices A, B, C, D, E, F and G.

Chapter VIII is devoted to analysis and evaluation of results, including type and location of improvements, cost, and levels of improved network efficiency. The relationship between improved efficiency levels and levels of capital invested is analyzed and evaluated. Different planning features explored in the application of the model are investigated. Relationships between investment programs generated by the model and resulting network spatial form are identified and explained. A number of alternative investment programs are compared and evaluated and from this conclusions are drawn concerning the relatively most cost effective investment program. The final section of Chapter VIII addresses the question: How far the solutions found are from the optimal ones? and, therefore, attempts to determine lower bounds by reformulating the road investment problem as an integer programming problem and solving it by linear programming. The section contains a full mathematical statement of the integer model, evaluation of the solutions of the original model with respect to the generated lower bounds, and from this conclusions are made concerning the general performance of the heuristic method in generating optimal solutions.

In Chapter IX, an attempt is made to link the results of the road investment programming model to changes in regional and national economy of the country. This is done through a discussion of the socioeconomic and policy implications of link improvements determined in the study for overall development of the Sudan. The discussion is presented in three sections that comprise the chapter. In the first and second sections, direct and indirect impacts of road improvement (e.g., costs, travel times, structure of the economy, urban development, national integration) are discussed. In the third section, current and future road planning and policies in the Sudan are examined. How these policies and planning practices could affect the implementation of the investment program proposed in this study and how the program can affect those policies and planning processes are examined. Accordingly, conclusions and recommendations concerning the investment program and planning process developed in the study are made.

Finally, an overall summary of findings, the limits and merits of the study and its planning method, and suggestions for further improvements and uses of the model, are provided in Chapter X. To the extent possible, the chapter indicates how several limitations can be removed by a change in the specification of the model and/or improvement in the input data base. It is hoped that future research on road investment modeling particularly for developing countries will suggest modification and improvements in the planning method developed and used in this study.

CHAPTER II

ROAD INVESTMENT PROGRAMMING: A REVIEW OF LITERATURE

Numerous models of optimal investment and road transportation network improvement have been developed for different purposes and situations. Most road investment modeling in developed countries has emphasized urban networks. Few researchers have considered the investment problem of interregional highways within developing countries.

Various classification of approaches to formulate the road investment problems have been suggested by researchers. One approach is to classify investment models into broad groups based upon the solution technique utilized such as linear programming, discrete programming, and so forth (43). Other approaches are based on narrowly defined criteria with respect to the objective function, such as the type of link cost function (23). In any case, the elements considered in these classifications reflect differing assumptions, primary objectives, and constraints used in investment models. In accordance with the purposes of the present formulation, a review of the literature is presented which focuses upon differences in objective functions, model assumptions and constraints. Criticism of these model features is evaluated in relation to developing countries. Because all of the studies of road improvement are too numerous to mention here, only representative ones, which are by no means exhaustive of the work done in this subfield of geography, will

be examined. For an extensive review of the many previous formulations, the reader is referred to MacKinnon and Barber (42) and Dantzig et al. (23). Pertinent studies dealing with road improvement in the Sudan are also briefly described in this literature review.

Differences in Model Objective Functions

Roads function to facilitate the movement of persons and goods among various places. The extent of this interaction will depend on the transportation cost, distance, or travel time between each pair of places. The potential for interaction increases with the decrease in distance, travel time, or reduction of transportation cost. Various objectives in determining road investment programming have been used in different formulations of road network improvement in metropolitan and regional systems. These objectives include: (1) minimizing total operating costs plus construction and maintenance costs, (2) minimizing total operating costs, and (3) minimizing investment costs.

Chapman (20), concerned with interregional road investment and development of an optimal road network in Oklahoma, formulated a linear programming model of investment in which the objective was to minimize the sum of operator's costs, construction costs, and maintenance cost. Quandt (48), Garrison and Marble (27), and Carter and Stewart (17), used linear programming formulations to determine investment and optimal allocation of funds for urban highway system improvements. All authors considered the objective of minimizing total vehicle operating costs and construction costs.

Roberts (50) and Barber (4) both considered the objective of minimizing total sum of construction and vehicle operating costs in their network improvement models for regional road network in Columbia. Their investment models were developed as mixed-integer (zero-one) programming problems where optimal link addition to the networks and optimal staging of investments were determined over a single and multiple time periods. Instead of considering investments only in the links, Barber, unlike Roberts, considered investments in both the links and the nodes of the network; considering both nodes and links allow road investment and productive capacity extensions to be made simultaneously.

Stairs (55) discussed the limitations of several methods used to solve the investment problem such as branch-and-bound and integer programming methods. He proposed an alternative method based on interactive computer programming and heuristic rules for solving the investment problem. To evaluate his method, Stairs applied it to an urban network improvement problem. In Stairs' formulation, user costs (defined as travel time) and capital costs were the evaluative criteria.

Bergendahl (9) attempted to generate the optimal time sequencing and size of investment with respect to the regional road network of southern Sweden. He used a multicommodity network flow linear programming formulation to determine, for each separate time period, the optimal network improvement which minimized total social costs (investment costs plus maintenance and vehicle operating costs) during that time. The minimum annual costs generated for each time period, and for

each feasible network, were then used as inputs in a dynamic programming formulation to obtain the overall optimal solution which minimized total social costs. Abdulaal and Leblanc (1) and Dantzig et al. (23), were concerned with the problem of extending the traffic assignment problem to an urban network investment problem. Abdullaal and Leblanc formulated a continuous unconstrained model to determine the optimal capacity increase of each link in the network subject to equilibrium flows where total congestion costs at equilibrium plus expenditure for improvement were minimized. Similarly, Dantzig et al. developed a continuous, but constrained, model where the optimal network improvement was based on minimizing total user and investment costs, using system optimal traffic assignment criteria.

In all of the preceding linear and integer formulations of the road investment problem, the objective function minimized is the sum of two sets of elements: operating costs (including accidents, time consumption, and other costs of operating vehicles) and investment costs (costs for new construction and other improvements to various links throughout the system). The objective in these studies represents a trade-off between capital costs on one hand and operating costs on the other; the solutions to the problems, therefore, traded-off increases in capital expenditure against decreases in operating costs on the other. Quandt (48) warned that when user and capital costs are lumped together, it would be difficult to provide criteria by which a dollar's worth of construction cost saved can be compared to a dollar's worth of transport costs saved. Also it has been observed elsewhere that since the

operating or user costs are often measured in units of time (converted to monetary units), the incorporation of the costs of network expansion directly into the objective makes the solution extremely sensitive to the assumed value of time. Because of these difficulties noted, the objective of minimizing total social costs or minimizing operating and construction costs to improve road network is not deemed an appropriate one for the present study.

To avoid the problems of lumping together user and capital costs, two alternative formulations for the road synthesis problem have been presented in the literature. In the first formulation, investment costs are minimized and operating costs or level of shipper service measures are used as constraints. The researcher in this case must specify an upper limit value on allowable user or operating costs. This approach has been used by Hay, Morlok and Charnes (30), and Chan (18). To find the minimum level of investment in the network required to meet some set of constraints might, in fact, be a more realistic objective for modernizing countries because they are characterized by shortages of developmental capital. Another advantage of this type of formulation is that the user cost constraint can be disaggregated into several different level of service measures. This helps to avoid dependence on factors to reduce all measures to monetary dimensions. The major problem with this type of formulation (in which investment costs are minimized and operating costs considered as a constraint), however, is that it places a requirement on the researcher to specify acceptable bounds for each of the level of service constraints to be employed.

Such bounds, as noted elsewhere, are often difficult to determine, and require fairly detailed information and analysis which may be unrealistic at the point in the planning process in which the overall network synthesis models are being used (57). The second approach to the road synthesis problem has been used by Barber (3), and Ahmed and O'Sullivan (2). Barber's model was originally formulated with the objective of minimizing total operating costs subject to a budget constraint. Then the model was modified by omitting the budget constraint and incorporating construction costs in the objective function. Ahmed and O'Sullivan's mixed-integer investment programming model was applied to the South Sulwesi region in Indonesia. The utilization of a mixed-integer algorithm and the backward dynamic programming technique permitted the authors to establish and evaluate the twenty-fifth year stage of investment programming and the resultant network for the region. The network configuration generated satisfied a given budget and the final traffic demand of the forty-sixth year at minimum total operating costs.

It should be noted that even where operating costs alone are considered in the objective function and capital costs in the constraints, the problem of sensitivity to the value of time discussed previously could not be entirely addressed. User costs themselves are multidimensional (including, among others, travel time, out-of-pocket costs, accident costs, and reliability of service), not always precisely defined, and typically measured in different units.

Continuous efforts have been made by researchers to overcome the problems of the time dimension. These efforts involve introducing some

conversion factors in order to retain the monetary dimensions of various costs when minimizing total operating costs, or amortizing investment costs on an annual basis using interest rates, discounts, inflation, and other time-dependent elements of capacity costs when minimizing joint costs of operations and investments (54). Despite these efforts, however, the problem is still that there is not widespread agreement on an appropriate and practical method for determining these time-dependent values in any given situation. Thus, a model which places emphasis on this value of time is open to serious criticism.

In view of the various difficulties involved in formulating the objective function of road network models as detailed in the foregoing discussion, it seems that the best approach for selecting a suitable objective in which those problems are avoided, is to keep operating and capital costs separate and to represent all operating costs by some function which could easily be measured. Such a function may be related to distance, speed, cost of travel, or others, which measure the level of service in the network links. This argument is especially true in the case of the Sudan where model operational feasibility and data considerations have a significant influence on defining an appropriate objective function. The difficulty of cost measurement makes it difficult to come to realistic investment decisions. This problem is made more complex in the Sudan by the absence of complete data in the country. Most researchers interested in developing countries generally and in the Sudan particularly have utilized cost data that are supplied from consultants and/or developed from international data bases; this

aspect has made the entire network evaluation and economic justification of investment based, at best, on general approximation. The road transportation system in the Sudan is composed mostly of earth roads; therefore, the system provides low quality of freight and passenger service measured in terms of low speed, high travel time, and risk of delays due to weather conditions. Many surveys of transport operation in the Sudan suggest that road users in the country weigh distance, time saved, and similar efficiency variables more heavily than costs per se (91, 95, 98). In application to road network of the Sudan and its improvement the present study, therefore, considers the objective of minimizing total weighted ton-kilometers so that overall road transportation system is as efficient as possible. The weighting factor can be used here to give different emphasis to different given classes of earth, gravel, and paved roads in terms of average travel time, average speed, degree of congestion, risk of delay due to weather conditions, and similar measures of network performance and quality of service offered by the road transport system. Minimizing total ton-kilometers on the basis of these weights implies, therefore, improvement in level of efficiency and, therefore, in overall level of service offered by the road transport system.

Assumptions and Constraints of Previous Road Transportation Models

The models discussed in the previous section assumed the existence of a capacitated network and/or that investments were to be made in new network capacity. The models and the investment contexts in which the

problem of capacity was treated (e.g., the strategy of minimizing investment costs, minimizing joint costs in the case of an inflexible budget, minimizing operating costs in case of a fixed budget) have already been discussed and will not be reiterated. Further discussion of these models and strategies is also available in Scott (54) and MacKinnon and Barber (41). What is of interest with respect to capacity, however, is the issue of the operational definition of link capacity itself and the various phases of its utilization in models of road investment generally.

Garrison and Marble (27), Quandt (48), Carter and Stowers (17), Chapman (20), and Bergendahl (8, 9), defined transportation link capacity, considered in terms of link addition (which is discrete variable), as a continuous variable. To allow discretely valued decision variable of investment in a continuous formulation and solve them as a linear programming problem would make such investment models subject to serious questions of validity. Can one add 2.3 lanes or 2.2 links?

To assume the existence of a set of discrete projects for improvement of the network seems to be more realistic in the context of integer formulations than in linear programming formulations. The problem, hence, becomes one of choosing a subset of these projects for implementation, and mixed integer (combinatorial) programming with a discrete variable for every link which can be improved is often used. The studies of Barber (3), Ahmed and O'Sullivan (2), and Roberts (50), are examples of this type of formulation. It has been noted that the

solution of discrete formulations is much harder than solutions of linear programming (58). Because of the integer variables, such problems are often approached using branch-and-bound techniques. Stairs discussed the limitations of branch-and-bound and integer methods of investment programming and contended that both methods have proved successful for only very restricted problems of small size (55). Boyce (11) noted that in large network improvement problems where one seeks to minimize total social costs, taking into account both link operating costs and link investment costs, branch-and-bound is not a feasible solution method.

In mixed integer investment formulations, the decision variable is constrained to be either zero or one. This implies that the whole link be added or nothing is done to a given link. I believe this strategy is inconsistent with conditions of developing countries, characterized as they are by shortages of developmental capital. Adding or deleting a whole link from investment consideration, for example, may cause substantial differences in the objective function as measured by money. In the former case, excessive investment may occur; in the latter, some important links may completely be neglected. In this research, investment decisions are taken to be the number of kilometers a particular road link is to be upgraded from one road surface type to the other. This strategy will allow some flexibility in making the necessary improvements in the road network to the desired level, i.e., to the whole link or a fractional portion of it.

The capacity assumption may not be consistent with real situations in developing countries. The problem of congestion reflected in

capacity constraints might exist in urban networks and/or in highways of developed nations. In most less developed countries like the Sudan, however, highways operate far below physical capacity. In fact some high standard modern roads in the Sudan were built in places where the average daily traffic was as low as 100 vehicles or less (99), evidence which indicates that capacity limits are not always a crucial factor used to justify improvements in the links. In the present investment program for the road network in the Sudan, therefore, no congestion effects or capacity constraint on any given road is assumed. Investment is measured not in terms of added or new capacity, but rather, in terms of improvement to the level of efficiency as measured by minimizing total weighted ton-kilometers on the basis of relative average travel time.

Summary of Literature Review

While most previous formulations of road improvement problems are attractive from a conceptual viewpoint, there have been some theoretical deficiencies and difficulties involved in respect to objectives, assumptions and constraints as shown in previous sections. This is especially true when one considers their application to developing countries. The problem of specifying an appropriate objective function has been noted by many researchers (including the present writer) as one of the major weaknesses in the current models of road network improvement (42). As MacKinnon and Barber put it, "There is an apparent need for models which are implementable, relevant, and about which we have some confidence regarding their validity" (42, p. 401). The present

formulation is an attempt to respond to such an expressed need. An interregional road network program is developed and will be applied to the Sudan. The goal is not limited to obtaining the actual optimal solution but also to achieve some insight into the network configuration over the existing Sudanese road system by applying the network model to a real world problem.

Studies of Road Improvement in the Sudan: A Review

In response to the need of rapid expansion of transportation facilities in the Sudan, a number of reports and studies have been recently completed in an attempt to find the type of improvements and quantity of investment needed to expand the country's transportation capacity. Most of these studies are transportation-oriented macro models of the economy. Lockheed (115) and Adar (103), for example, made comprehensive studies of all the transport modes vis-a-vis the future transport requirements of the economy. Very limited work has been done with respect to road development independent of other modes in the Sudan.

The United Nations study, Development of Roads in the Sudan, was done by J. A. Campbell in 1957 (107). In his final report, Campbell set forth the road needs of the country and their costs. He recommended construction of a major national and regional network of roads, and he called for an extensive system of new roads. In identifying the road projects, Campbell made arbitrary decisions based on sufficiency ratings and engineering judgment.

In 1973, Louis Berger, Inc. (116) conducted a series of studies of highway development in the Sudan covering the period from 1973-1993. A part of the series was an emergency maintenance program and another was a study done of priorities for road construction and improvement, standards for design of those roads, and selection of a budget for the period of construction. Utilizing benefit-cost methods to evaluate investment decisions on projects, Berger was able to identify a national system of roads which link the main centers of population, development, government administration, and form major international connections. Rankings and establishing priorities of the projects for implementation were determined by using the benefit-cost ratio.

In both the United Nations and Berger studies the analyses were conducted within a context of mutually exclusive projects. No concern was expressed for the relationship among the road projects or the effects of improvement in the road system on overall efficiency of the network. In this study, investments towards upgrading various road types are made so that overall road transport is efficient (i.e., minimizes total weighted ton-kilometers).

Using the Sudan as a study area and information source in 1961, Betz (67) analyzed the relationship between transportation costs and the amount of traffic. He developed a mathematical model based on total social costs minimization to determine both the location and types of transportation facilities needed for various levels of capital investment. Unfortunately, the paucity of data in the Sudan led Betz to formulate his model with data calibrated largely from other African

countries such as Nigeria and Ghana. These data, in one way or another, may not be relevant to the Sudanese situation. It was this data problem which caused the goal of the Betz's study to be shifted from concentrating on a plan for transport investment in the Sudan, to a methodology which serves only as a guide in transportation planning for developing countries in general. In this way, Betz failed to provide any useful conclusions with respect to transportation and its improvement in the Sudan.

Other studies on road improvement in the Sudan have been made. These are couched, however, in either a project by project basis, or they are feasibility studies for individual road projects.* Generally, in most of these studies the use of a specific road is considered in isolation from the whole road network and no overall concern was given for the relationship among all the roads. The larger problem of the layout and use of an entire road network in the Sudan, however, is interesting in a system's context. Viewing the entire system comprehensively, which is the attempt of this study, permits more meaningful analysis of the location and locational effects of improvement in the road system as a whole than is possible if only individual roads are considered in isolation from the remainder of the road transport system.

Overall Summary of Literature Review

While much theoretical work concerning road development in the Sudan and other countries has been done, much remains to be accomplished

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*Some of these studies are listed in the bibliography.

in the practical application of these models to real transportation network. It is my nearsighted opinion that road investment models, whether developed for modernized or modernizing countries, in regional or urban contexts, should be formulated with real world problems in mind. In formulating the present improvement program, consideration was given to the operating conditions and characteristics of the road transportation network and the economy of the Sudan; the model represents the operation of a realistic transportation network, and it avoids many of the noted inadequacies in previous formulations. This model may turn out to be highly practical. Also the model may turn out to be appropriate and implementable to other developing countries given appropriate data specification.

CHAPTER III

SPATIAL DISTRIBUTION OF POPULATION AND ECONOMIC ACTIVITIES IN THE SUDAN

This chapter analyzes the regional economic framework within which the interregional road system of the Sudan is cast. The location of the country's population and of productive activities are crucial determinants of transportation needs. Each productive factor and its regional distribution is treated separately here. Particular emphasis is given to agriculture (including livestock and forest products) and the industrial sector because the bulk of freight traffic in the Sudan is generated by commodities related to these two sectors. Agriculture production and inputs, transportation of consumer goods, either those that are imported or locally produced, together with movement of exports, account for most of the volume of truck traffic.

The analysis is done within the framework of the ten provinces that existed in 1974. Figure 1 shows the location of the ten provinces as they were delimited in 1974. They are Northern, Khartoum, Blue Nile, Kassala, Red Sea, Kordofan, Darfur, Upper Nile, Bahr El Ghazal, and Equatoria. Although provincial boundaries in the Sudan are based on political criteria, in most cases they conform to economic, cultural, and physical criteria as well. The ten provinces can, therefore, be treated here as ten meaningful geographic regions of analysis. There are similarities among some of the regions as well, so that they might be aggregated for the purpose of discussion without doing violence

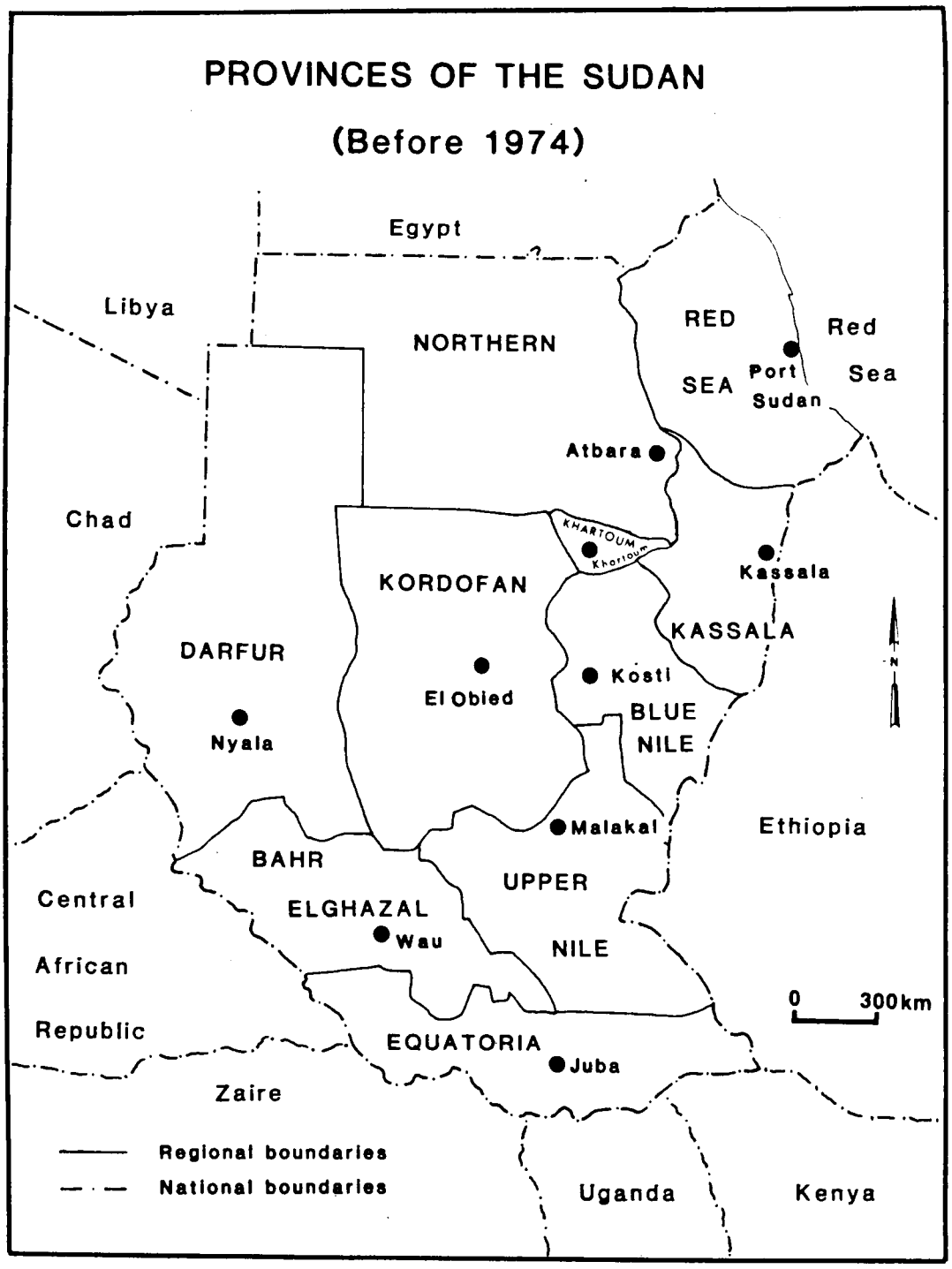


Figure 1. Provinces of the Sudan (before 1974).

to the breadth of geographic variability within this large country. These similarities relate to distance from markets, general location, type of products produced, and similar ecological and developmental factors that exist among some of the provinces. In such circumstances, two or more provinces may be grouped and treated as one region. For example, Bahr El Ghazal, Upper Nile, and Equatoria are located in the southern part of the country; and may be referred to generally as the "Southern region." Similarly, Darfur and Kordofan may be referred to as "Western Sudan"; Kassala, Khartoum, and Blue Nile as the "Northeast" or "Central Sudan."

Pattern of Population Distribution and Growth

The first modern population census in the Sudan was carried out in 1955/56. Total population was estimated to be 10.3 million. The second census took place in 1973 and indicated a population of 14.9 million. The rate of growth of population for the country as a whole for the intervening seventeen year period was 2.2% per annum, made up of a growth rate in urban areas of 7.4% per annum and in rural areas of 1.5% per annum.

The regional distribution of population in the Sudan for 1956 and 1973 is compared in Table 1. In both periods the major concentrations of population were in the Blue Nile, Kordofan, and Darfur provinces. In 1973, close to 40% of the country's inhabitants lived within the two agricultural regions of the Blue Nile and Kordofan alone. Between 1956 and 1973 the annual population growth rate in the Blue Nile (3.6%) was

Table 1

Area, Population, and Density in the Sudan by Province in 1955/56 and 1973

Province	Area (sq. km.)	Population (000's) 1955/56	Population (000's) 1973	% Average Rate of Growth per Annum	Density (persons/km²) 1955/56	Density (persons/km²) 1973
Blue Nile	142,138	2,069.4	3,812.9	3.66	15	28
Khartoum	20,971	504.9	1,168.2	5.06	24	53
Northern	477,074	873.0	998.9	0.9	2	2
Kassala and Red Sea	340,655	941.0	1,588.5	3.13	3	5
Kordofan	380,546	1,762.0	2,202.3	1.32	5	5
Darfur	496,369	1,328.8	2,181.1	2.96	3	4
Bahr El Ghazal	213,751	999.0	1,396.9	1.99	5	6
Upper Nile	236,180	888.6	798.2	-0.63	4	3
Equatoria	198,121	903.5	755.7	-1.05	5	4
Total	2,505,805	10,270.2	14,902.7	2.2	4	6

Source: Sudan Department of Statistics, Statistical Book, Khartoum, Sudan, 1973.

second only to that of Khartoum (5%). The Southern region, especially Equatoria, registered a negative growth rate because of political instability that prevailed up to 1973 in southern Sudan; the Department of Statistics estimates a current 2.5% growth rate for the Southern region as a whole (114). The average population density in 1973 was 6, 28, and 56 persons per square kilometer for Bahr El Ghazal, Blue Nile, and Khartoum, respectively; each of the remaining seven regions have a population density below the national average (about 6 persons per square kilometer).

The percentage of urban population rose from 8.3% in 1956 to 18% of the total population in 1973; but recent statistics indicate that this percentage has reached 29.4% (99). The population of Khartoum alone represents 30% of the urban population in the Sudan, followed by Blue Nile, Kassala, Red Sea, and the Southern region. Seventy percent of the population of Khartoum region live in urban areas, followed by the Red Sea (34%), Kassala (21%), Northern (18.1%), Darfur (13.5%), and Blue Nile (6.1%) (99). The rate of annual increase in urban development in the whole country between 1956 and 1973 was 5.4% with Khartoum registering for the highest annual rate of increase (6.4%), followed by Darfur (5.9%), and Kassala (5.6%). The southern three regions registered a combined annual urban growth rate of 38.1% during the same period (99).

In 1973 the number of people migrating between the various regions amounted to 1.2 million persons whereas in 1956 the number was only 0.4 million. The Khartoum region represents the major attraction area

for the migrant population (30.6%) followed by Blue Nile (29.7%), and Kassala (10.7%). The areas of greatest out-migration are the Kordofan region (27% of the emigrants), the Northern region (22%), and Darfur region (20%). For the whole country the rate of migration towards the rural areas reached 5.6% of the total number of migrants across the regional borders (99). These figures, however, do not include internal migration within the regions or nomadic movements or seasonal labor migration. The number of seasonal (temporary) migrant workers is relatively large, comprising 14% of the total labor force (7 million) or 6.5% of the total population of the country (90). Because seasonal migration has a direct effect on road transportation demand, it will be analyzed in the context of traffic movement in another chapter. The highest percentage of the migrants are aged 20-39 (47.1% of the total urban migrants); 14.9% of the total urban migrants are in the 25-29 age group (99).

The population distribution in the Sudan is uneven, and differences in population densities and growth rates among regions are relatively large. Population concentrations are quite spatially separated from each other. Also the population of the Sudan is highly mobile with young people having the highest likelihood of mobility to urban areas. Finally, the major interregional migration streams in the Sudan are from the northwest origin areas to the northeast destination regions where many major agricultural and industrial projects are located.

Distribution of Agricultural Activities in the Sudan

From a total land surface of 238 million hectares (ha.), 84 million hectares could be used for agriculture in 1975 (Table 2). This represents four-fifths of the Arab world's cultivable land (123). At present, however, only 3.3% of total land area (9.3% of total cultivable land) is actually cultivated.

Agriculture in the Sudan occurs in two types of settings: modern and traditional. The modern sector is highly organized and includes large scale mechanical irrigation projects as well as smaller scale pump schemes along riversides, and large scale mechanized farming under rainfed conditions. The modern sector accounts for more than 80% of the value of the country's total agricultural products. The second sector contains the traditional rural population cultivating small holdings mainly under rainfed conditions and using manual techniques. A total area of about 4.2 million ha. (54% of total land area devoted to agriculture) is at present under this type of agricultural activity. Most of the traditional agricultural areas are directed towards subsistence production.

The agricultural expansion program envisaged in the Six-Year Plan (1977-1983) laid special emphasis on increasing crop productivity by modernization and intensification of cultivation in the irrigated areas. Provision has also been made to initiate massive semiprivate projects for rainfed mechanized cultivation in the Blue Nile, Kordofan, and Darfur regions as well as the northern parts of Bahr El Ghazal. In

Table 2

Land Utilization in Sudan 1975

	Areas	Hectares (000's)
I.	Total Area	250,581
	1.1 Land Area	237,600
	1.2 Area Under Water	12,981
II.	Agricultural Area	84,000
	2.1 Cultivated	7,848
	2.10 Cropped	7,008
	2.101 Irrigated	1,565
	2.102 Unirrigated	5,443
	2.11 Fallow	840
	2.2 Uncultivated	76,152
III.	Pasture Land	24,000
IV.	Forests	91,500
V.	Other Uncultivable	38,100

Source: Sudan Ministry of Agriculture, Food and Natural Resources, Sudan Year Book of Agricultural Statistics (and Supplement for 1979), Khartoum, Sudan, 1977.

addition, modernization of traditional farming is encouraged in the development plan to increase the agricultural productivity. The planned self-sufficiency program is aimed at expanding wheat, tea, and coffee production to meet local demand by 1983. Agricultural policies are aimed at the diversification of crops for export as well as for local processing industries. Special emphasis is placed upon increasing the meat exports by establishing modern ranches and upgrading the quality of meat.

Arab oil countries have begun to invest in Sudanese agriculture in what eventually will total billions of dollars and Western companies have begun to supply farming know-how and management in hopes of raising agricultural productivity 80% in ten years (64). A large number of agricultural projects have, therefore, been either established or planned for long-term benefits. Figure 2 shows the distribution of agricultural resources and location of some proposed and existing agricultural projects in the Sudan. According to one projection, the Sudan by 1985, will be providing 42% of the Arab world's total vegetable oil consumption, 58% of its meat, and 20% of its sugar needs; altogether a 300% boost in agricultural exports (64).

Agriculture in the Blue Nile region. Blue Nile is by far the most important agricultural region and one of the richest in livestock. The region possesses about 22% of total livestock in the country, mostly sheep. Most of the country's commercial cash and food crops are grown here. The region is known as the "granary of the Sudan" (81). At present about 85% of the land being irrigated in the Sudan is in this

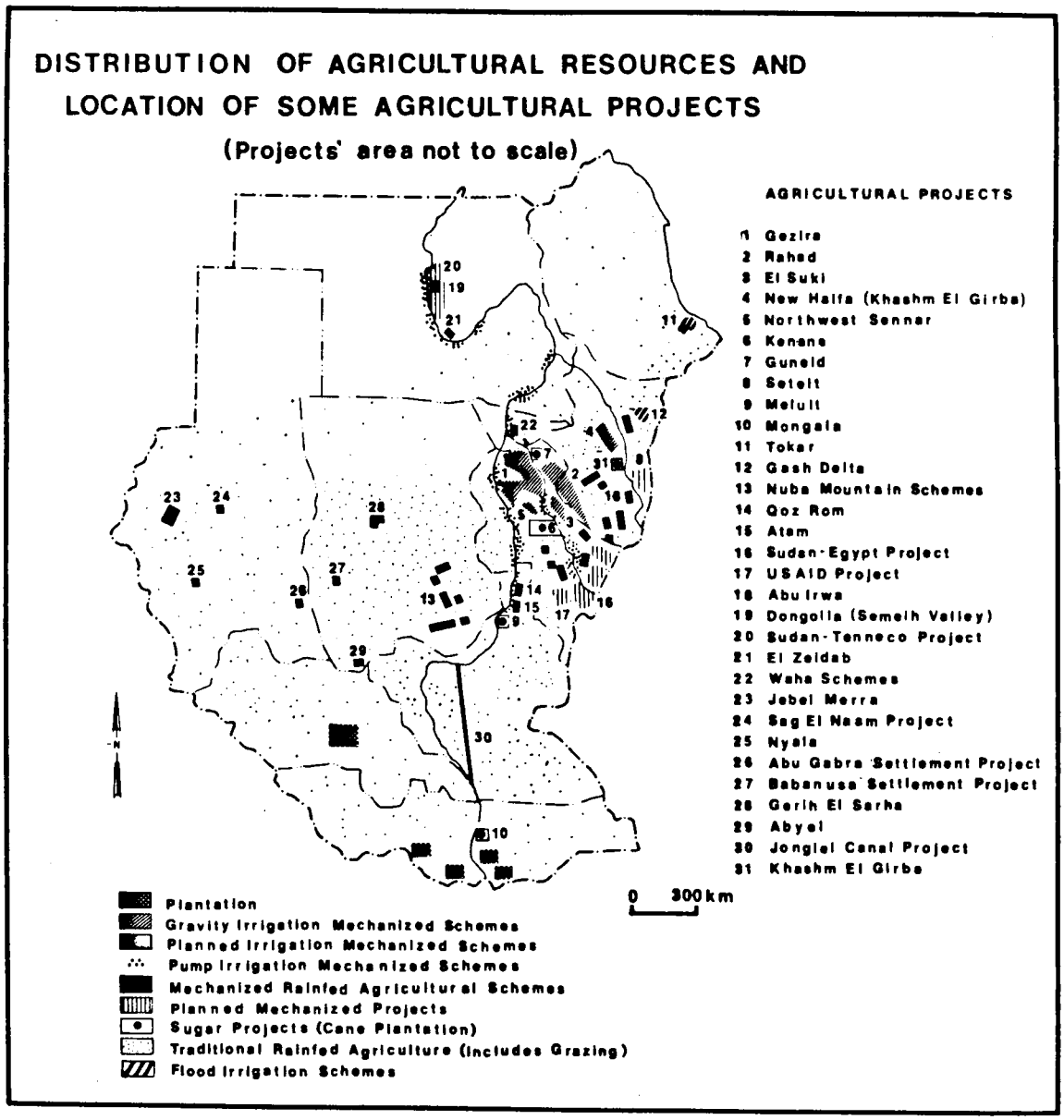


Figure 2. Distribution of agricultural resources and location of some agricultural projects.

region including most of the largest schemes in the country such as the Gezira (882,000 ha), Kenana (33,000 ha.), and Northwest Sennar Scheme (22,680 ha.) (see Figure 2). The latter three are sugar plantation schemes. Short and medium-staple cotton as well as long-staple cotton for which the Sudan is the second largest supplier to the world market, groundnuts, wheat, sorghum, rice, fruits and vegetables, are some of the most important crops grown in these schemes.

Extensive pump irrigated schemes extend to the southern parts of the region on both sides of the Blue and White Nile rivers. According to recent (1980/81) statistics, this irrigated area had expanded to 687,000 ha. (104). Cotton, groundnuts, and sorghum are the main crops grown on this irrigated land. Also the extensive schemes of mechanized rainfed agriculture lie in the southern reaches of the region with an area estimated at about half a million hectares. Most of the region's sorghum and sesame is grown here.

Compared to other regions, Blue Nile accounts for the largest percentage of agricultural output in the Sudan. It accounts for 85%, 85%, and 45% of the Sudan's total production of cotton, wheat, and sorghum, respectively. Table 3 shows production figures for some of the major crops grown in the Blue Nile region.

Even though it is already the most developed region among all regions of the Sudan, Blue Nile has the best development prospects. Government effort has been made recently to expand and further develop potential agricultural resources in the region. The Rehabilitation Program (commencing in 1980/1981) was designed to help increase productive capacity of all irrigated schemes in the region. Plans for the

Table 3

Production of Some Main Crops and the Number of Livestock in the Blue Nile Region (1978-1979)

Crops			Livestock (in 000's head)			
Crop	Area in ha.	Production in tons	Cattle	Sheep	Goat	Camel
Cotton	33,480	356,000	3,071	4,817	2,562	267
Sorghum	940,800	828,000				
Sesame	186,060	63,000				
Groundnuts	148,680	248,000				
Rice	1,680	5,000				
Maize	17,640	12,000				
Wheat	215,460	154,000				
Sugar Cane	8,400	530,000				
Millet	84,840	38,000				

Source: Compiled from Sudan Ministry of Agriculture, Food and Natural Resources, Sudan Yearbook of Agricultural Statistics (and Supplement for 1979), Khartoum, Sudan, 1979.

Gezira scheme, for example, are to extend cropping area by 10% through fallow reduction and 50% in average yield through higher levels of fertilizers use and better mechanization techniques. Particular emphasis is on increased yields of cotton and wheat. An expansion of over 100,000 ha. in intensive mechanized crop production scheduled over the next decade will concentrate on sesame, cotton, and sorghum.

Many foreign-financed development projects are planned in the Blue Nile region. All these foreign developments will boost agricultural production in the region and will add a new dimension to the existing structure of agricultural production in the region. Of particular importance is the introduction of livestock and dairy products. It is generally estimated that about 70% of total output of most of these projects will be exported (118).

Agriculture in Kassala region. The Kassala region has a relatively well developed agricultural base. Irrigated agriculture is confined to three areas. The Gash delta scheme extends northwards from the city of Kassala. Sorghum and castor seeds are grown in this project. Virtually all Sudanese production from castor seeds is produced in this flood irrigation scheme. The New Halfa project is at present the third largest irrigated scheme in the country, extending over an area of 210,000 ha. This includes 40,000 ha of sugar cane production, 15,000 ha. of freehold land devoted to fruits and vegetables, and the rest is devoted to cotton, groundnuts, and wheat of which the scheme is a major producer. The third area of irrigated agriculture is sustained by an aquifer, underlying a small hill (jebel) upon which the city of

Kassala is situated. An intensive market gardening area has developed in the vicinity of the city.

The Kassala region is the largest center of mechanized rainfed farming in the Sudan, principally in the Gedaref district. Some 840,000-1,260,000 ha. are now cropped annually, an area that represents almost 63% of total land devoted for mechanized rainfed cultivation in the country. Sorghum is the primary crop with sesame as secondary. The region shares first position in sorghum production with the Blue Nile region. About 31-40% of total sorghum production in the country is produced in the region of Kassala. Table 4 provides area and production figures for some of the major crops produced in the region.

The agricultural areas discussed above cover about one-third of the Kassala region. The remaining two-thirds are given over largely to a traditional livestock economy and is considered unlikely to be the focus of major traffic generating activities in the near future. The scope for further area expansion of agriculture in the Kassala region is limited to the south by a national game park (in the Blue Nile region), to the east by the Ethiopian border, and to the west by the irrigated Rahad scheme. Despite these physical limitations, however, there is still ample room for further expansion of agriculture. At present the only major new project envisaged for the region is the Seteit irrigation scheme which would command some 210,000 ha. The earliest completion date for the required dam at the Seteit River would be 1986 (118, vol 1, part C).

Immediate development prospects of the Kassala region lie in the recent Rehabilitation Program to help increase production capacity of

Table 4

Production of Some Main Crops and the Number of Livestock in the Kassala Region (1978-1979)

Crops			Livestock (in 000's head)			
Crop	Area in ha.	Production in tons	Cattle	Sheep	Goat	Camel
Sesame	86,520	22,000	665	1,701	990	579
Groundnuts	13,400	10,000				
Wheat	17,640	9,000				
Millet	2,100	1,000				
Sorghum	885,360	735,000				
Cotton	41,580	27,000				
Sugar Cane	9,240	838,000				
Castor	195,720	16,000				
Onions	420	8,000				

Source: Compiled from Sudan Ministry of Agriculture, Food and Natural Resources, Sudan Yearbook of Agricultural Statistics (and Supplement for 1979), Khartoum, Sudan, 1979.

existing irrigated schemes in the region. An investment of L$35.75 million, which over five years would raise productivity of the New Halfa scheme over its present level through both area extension and yield improvement, is already underway. Upon completion, this program is expected to raise crop yields in the New Halfa project area by 65%, thereby increasing output of cotton and groundnuts. It will also bring 72,600 ha. of currently uncropped irrigable land into production.

Agriculture in the Western Sudan region. In Western Sudan (Kordofan and Darfur) irrigation systems are not yet available. The population is engaged mainly in traditional farming under rainfed conditions and mixed cropping is widely practiced. The introduction of cotton earlier in the century and the more recent work of the Nuba Mountain Agricultural Production Corporation in introducing mechanized land preparation into small holdings has given many of the farmers (especially in Kordofan) a cash crop orientation. About 21,000 ha. are presently under cultivation, mainly sorghum and sesame, on an official mechanized farming scheme. Another 10,500-12,600 ha., constituting the Nuba Mountain projects, are modernized programs which grow cotton and sorghum. The largest modernized scheme in Western Sudan, comprising an area of 88,620 ha. has recently been established, producing about 64,000 tons of sorghum and sesame and a little cotton. In 1980 another 22,680 ha. were added to this scheme. Another 18,500-37,000 ha. in mechanized schemes extending over the border of the region to adjacent mechanized schemes in the Blue Nile and Upper Nile regions have been demarcated for future development. Other than these rainfed mechanized

schemes, agriculture in Western Sudan is based entirely on rainfed nonmechanized farming methods.

The principal cash crops of Western Sudan are groundnuts, sesame, and gum-arabic which is tapped from a species of acacia tree. The region is responsible for nearly 60% of the country's total production of groundnuts. Half of the total production is exported and the other half used in the production of oil and oil cakes. Also the region is the largest producer of gum-arabic and sesame in the country, producing almost 90% of total gum production and 40% of total sesame production in the Sudan. These two crops are, in fact, leading crops in Sudanese exports. A fair amount of cotton, tobacco, and a few other cash crops like watermelon seeds and Karkadeh, are also produced in the region (mainly in Kordofan). Also, food crops, especially sorghum and millet, are grown in virtually all the districts of the region for subsistence. Nearly all of the country's millet production (90%) is confined to Western Sudan (Table 5).

The Western region encompasses most of the land used for grazing in the Sudan. About 38% of the country's livestock resource is found here, mostly cattle and sheep. Most of the livestock resource in the region is owned by nomads who move south and north as the seasons change and is, therefore, not under full commercial exploitation. Other agricultural resources of the region are forests of which the Western region ranks second among all other regions of the country. Forests in the region comprise 29.3% of the total forested area in the country, most of which is concentrated in the southern parts of the area.

Table 5

Production of Some Main Crops and the Number of Livestock in the Western Sudan Regions of Kordofan and Darfur (1978-1979)

Crops			Livestock (in 000's head)			
Crop	Area in ha.	Production in tons	Cattle	Sheep	Goat	Camel
Groundnuts	721,140	473,000	6,259	6,378	5,018	1,247
Sesame	467,040	99,000				
Millet	1,166,340	491,000				
Sorghum	704,760	514,000				
Cotton	50,400	18,000				
Maize	4,620	3,000				

Source: Compiled from Sudan Ministry of Agriculture, Food and Natural Resources, Sudan Yearbook of Agricultural Statistics (and Supplement for 1979), Khartoum, Sudan, 1979.

Although the future prospects for expansion of agriculture and livestock is quite favorable in Western Sudan, very limited expansion efforts have thusfar been made. The government is aiming to transform about 126,000 ha., currently under traditional subsistence farming in Kordofan, into modern mechanized schemes (118, vol 2, part C). Some recent development programs, funded mainly by the European Development Fund, concentrate on the Jebel Merra area northeast of Darfur region, for the production of fruits and vegetables and possible tourism development. Another development program sponsored by the United Nation's Western Savannah Development Project is currently being undertaken to increase yield and area of production in already existing schemes. Other development programs supervised by the United Nations agency involve development of ranching units to settle the nomads of the region. Many of these ranching projects have already begun. One major problem which might handicap agricultural expansion is that the rangeland in southern Darfur is threatened by desertification as a result of both climatic change affecting the whole of the Sahel area of Africa and of overgrazing. Some recently available statistics show that crop yield has been decreasing for the last few years in Western Sudan because of these environmental problems (59).

Agriculture in the Northern region. Being mostly desert, the Northern region is agriculturally less productive than the other regions discussed thus far. Agriculture is possible only along a narrow strip adjacent to the Nile River, irrigated by pumps or flood. Rainfall farming is virtually impossible. The agricultural economy of the region

is dominated by commercial food crops which cover over three-fourths of the net area sown. The region, therefore, is one of the deficit regions in food crops and shortages are often relieved by surplus production in other regions of the country.

Horticulture is a dominant type of agriculture in the Northern region. There are about 1,830 irrigated schemes devoted to horticulture and subsistence farming encompassing over 330,000 productive ha., including the date reserve. There are an estimated 2 million date palms in the region, producing roughly 250 pounds of dates per tree (81). Associated with the horticulture schemes are approximately 144,850 ha. of nonproductive land or land under subsistence farming. The main crops grown in the region are dates, pulses, alfalfa, mangoes, grains, sorghum, cotton, and citrus. Wheat is produced on the pump schemes and is grown as a winter crop. Until recently, all production of wheat in the country was confined to this region and it has been the region's principal cash crop (Table 6).

As part of the Sudanese strategy for accelerating the development of modern food system in the country, an ambitious scheme with a price tag of 1 billion American dollars to develop 313,875 ha. began in 1977. The program, sponsored by the American Company, Tenneco, is to be developed over a 15-year period. About 101,250 ha. are planned to be under irrigation and intensive mechanized methods of farming along 80 km. of the east bank of the Nile River. Then 202,500 ha. are to be added at later stages of planning. Initially the project will emphasize nonperishable commercial food crops, with a strategy of continued

Table 6

Production of Some Main Crops and the Number of Livestock in the Northern Sudan Region (1978-1979)

Crops			Livestock (in 000's head)			
Crop	Area in ha.	Production in tons	Cattle	Sheep	Goat	Camel
Haricot Beans (Fasulia)	2,520	4,000	60	511	437	170
Horse Beans (Ful Masri)	13,020	21,000				
Wheat	12,600	14,000				
Sorghum	21,000	20,000				
Chickpeas	2,520	3,000				
Maize	2,940	3,000				
Onions	2,520	10,000				

Source: Compiled from Sudan Ministry of Agriculture, Food and Natural Resources, Sudan Yearbook of Agricultural Statistics (and Supplement for 1979), Khartoum, Sudan, 1979.

transition of the cropping patterns between nonperishable and perishable and between types of perishable crops as dictated by market demands (102). The food program will expand total cultivated area in the whole country by more than 4%, help build a solid base for future development of agriculturally-based industry; and when completed, will be capable of producing 3.5 million metric tons of grain equivalent annually.

Agriculture in the Southern region. The Southern region remains the most backward in terms of agricultural development. It is estimated that an aggregate of 799,000 ha. are under crop cultivation most of which is based on a traditional system using hand tools and shifting cultivation or rotational grazing (120). Although the land devoted to agriculture is fairly evenly distributed among the three regions of southern Sudan, development of modern mechanized cultivation is so far restricted to the northern part of the Upper Nile region, and to the rice plantation schemes of Bahr El Ghazal. Of the Upper Nile's total area of a quarter of a million hectares, about 60% is reported to be under mechanized cultivation (120). In the Equatoria region the area under mechanized cultivation amounts to no more than a few hundred hectares.

Mixed cropping is widely practiced in the Southern region and most of the production is for subsistence use. Sorghum is predominant, accounting for 40% of total crop area. Millet and maize occupy a secondary position. The production of cassava is spreading in most areas but reaches its greatest importance as a food crop in the Equatoria region. Cotton is a significant cash crop in the Equatoria

region with total area of 3,300 ha. and rice is becoming increasingly important (Table 7). Also, the Southern region commands 43.3% of total area covered by forests in the country and 36.1% of national livestock resource. The region is particularly rich in cattle, possessing about 7 million head concentrated mainly in the Upper Nile and the Bahr El Ghazal regions.

The agricultural potential of the Southern region appears to be impressive, though yet only marginally developed. A number of development projects are in various stages of completion in the region. There are 786 nonmechanized development schemes (630 ha. each) established in the Upper Nile region (118). A 6,300 ha. mechanized farm has been established in the Equatoria region to produce sorghum and this area is planned for expansion to 12,600 ha. during the Six-Year Plan period 1977-1983. There are definite plans to develop 33,600 ha. in the public sector during the current planning period (1977-1983) throughout the Southern region for the production of sorghum, sesame, soybeans, cotton, tea, coffee, and tobacco. The IBRD's Agricultural Rehabilitation Project has the four year objective of developing more than 3,150 ha. in the Equatoria region with a target production of 1,000 tons of coffee by 1980 (118). In the Six-Year Plan, another program, backed by Arab funds, has set targets for 1982-83 that range from 3,360 to 6,300 ha. producing 10,000 tons of coffee. Also in accordance with guidelines of Sudanese development strategy that is based upon the theory of import-substitution, production of tea is expanding (91). Current plans incorporate targets of cropping 2,400 ha. of land by 1982-83 and

Table 7

Production of Some Main Crops and the Number of Livestock in the Southern Sudan Regions of Equatoria, Bahr El Ghazal and Upper Nile (1978-1979)

Crops			Livestock (in 000's head)			
Crop	Area in ha.	Production in tons	Cattle	Sheep	Goat	Camel
Sorghum	438,480	275,000	5,753	3,412	2,333	34
Millet	317,100	12,000				
Rice	6,720	5,000				
Maize	37,800	30,000				
Groundnuts	82,320	60,000				
Sesame	69,300	27,000				
Cassava	33,600	92,000				
Coffee	420	500				
Tea	Less than 420	Not Available				

Source: Compiled from Sudan Ministry of Agriculture, Food and Natural Resources, Sudan Yearbook of Agricultural Statistics (and Supplement for 1979), Khartoum, Sudan, 1979.

long-term targets of 26,000 ha. have been set for tea production. The aim of expanding the area devoted to tea plantations is to meet increasing domestic demand which reached 17,000 tons in 1976 (120). Tobacco production will also be expanded to 1,600 tons by 1983. Another cash crop considered for expansion in the region is rice. In the Upper Nile and Bahr El Ghazal regions the government has set a combined target production of 20,000 tons of rice per year. Production of fruits, vegetables, and spices is limited in the Southern region but a wide range of tropical fruits can be grown without irrigation, especially citrus fruits, mango, banana, and pawpaw (120). Particular attention is being focused on pineapples in development schemes especially in the Equatoria region where the best fruit potential exists and it is likely to be the focus of any processing industry that might develop. In general, a total of 642,000 ha. throughout the Southern region have been proposed for agricultural expansion of which 105,000 ha. are allocated to Equatoria. A further 105,000 ha. is earmarked for the Bahr El Ghazal and Upper Nile regions (120).

Livestock development programs in the Southern region have so far concentrated on improvement of animal health but there are plans for improvement of grazing control schemes and development of commercial ranching and marketing systems. The IBRD-financed Agricultural Rehabilitation Project, for example, has an objective of improving livestock marketing conditions. A modern 200,000 ha. ranch is planned to act as a feeder to a meat processing complex with a target of supplying 15,000 head per year (120). This project is, however, to be

developed over a 30 year period. Pilot livestock ranching schemes are under development such as the one in the Bahr El Ghazal region which is designed to cover 10,000 ha. and ultimately carry 1,000 livestock units. The aim of these schemes is to develop an integrated ranching industry in the Southern region.

Finally, one of the main development projects in the Southern region is the Jonglei canal. This is a scheme to build a 320 km. canal in the Sudd region, from the town of Bor to a point on the White Nile south of Malakal (see Figure 2, p. 40). The project is intended to increase the volume of water in the Nile that can be used for irrigation by both the Sudanese and Egyptian people. The Jonglei canal will provide water to about 81,000 ha. of cultivable land in the Southern region and promote the settlement of some 350,000 Nilotic tribesmen, most of whom are at present leading nomadic life. The scheme will, therefore, provide the inhabitants of the region with opportunity for growing cash crops such as cotton, coffee, palm oil and rice, as well as better grazing for their cattle, sheep, and goats. The canal project is expected to be completed by 1990. The effect of the canal upon the pattern of road investments is not considered in the model developed in this study.

Agriculture in the Khartoum and Red Sea regions. The Khartoum and Red Sea regions do not contribute a significant amount of agricultural production on the national scale. Khartoum is a metropolitan region and mostly supplies fresh fruits and vegetables to the region itself. The Red Sea region grows a little cotton, sorghum, and millet with

production of 4,000, 32,000 and 8,000 tons, respectively, in 1978-79. The region's importance, however, lies in its export-import activities since the only sea port of the country is located in this region.

Distribution of Industrial Activity in the Sudan

Existing Sudanese industries can be divided generally into two broad categories according to the forces that influence location, i.e., market-oriented industries and raw material-oriented ones. The market-oriented group contain the largest number of establishments but are generally smaller in size and, therefore, in volume of production when compared to the raw material-oriented group. These market-oriented industries locate in proximity to urban markets, mainly Khartoum. Some industries of this group produce weight-gaining commodities and their location is, therefore, influenced by transportation costs. The group include industries like soft drink bottling, printing, soap manufacture, footwear production and confectioneries. Industries that are attracted to the source of raw material, often are weight-losing and/or use perishable raw materials. Most of these industries require processing near production sites. Raw material-oriented industries represent the most important industries in the Sudan. They include sugar refining, food oil, textiles, cement, and foodstuffs.

Recently, the Sudan has embarked upon developing a comprehensive industrial development program. Emphasis of priority has been given to self-sufficiency in basic consumer goods such as sugar, textiles, wheat flour, sacks, paper, cigarettes, ready-made clothing, and canned fruits.

These items account for close to one-fourth of the imports of consumer goods. Also special attention has been accorded to export-oriented industrial production especially food oil and hides and leather products. In connection with the program, 423 private sector enterprises have been implemented in diverse areas of manufacturing. Public sector projects being implemented are heavily concentrated in sugar factories and weaving. In total, 24 separate public sector projects are included in these plans (75). Despite the relatively small number of manufacturing industries in the country, Sudanese industries are not all small scale activities. A handful of establishments are of good size even by American standards. For example, the Sudan Cotton Textile Company, located in Khartoum, employs over 8,000 workers. Excluding this company and a few others, however, the number of workers per establishment in each of the 822 existing establishments range from 35-500 workers.

Edible oil products are the country's main industrial export. At present oil factories and mills are working at a capacity of 875,000 metric tons per year, but with the new oil factories currently under construction this capacity will be raised to about 1.5 million tons in 1983, an increase of 8% (121). In 1979, three sugar factories were in operation with total production of only 132,000 tons which was far below full capacity. Today six factories are producing but no production figures are currently available. With the additional three proposed sugar factories, however, total production of sugar is expected to reach 1.2 million tons by the mid 1980's (93, 110). In 1979, about 235,200 tons of flour were produced in the Sudan. By 1983 the country is

expected to produce 3.8 million tons of flour annually because of improvements in production capacities and installation of new flour mills.

Regional distribution of industry. Industry in the Sudan is concentrated in a few regions. Dispersion of industry in the country is limited by the industry type and its relative advantage in location with respect to raw materials or markets. Only 10% of industrial investment can be regarded as footloose in the sense that a variety of locations can be considered (75).

Table 8 shows the regional distribution of industries in the Sudan in 1977. About 70% of total industrial establishments are located in the region of Khartoum alone. The rest are distributed throughout the remaining nine regions. Most of the market-oriented industries are located in Khartoum; but also the region is a major center of textile, weaving and spinning industries.

The Blue Nile region is the second largest industrial region in the country. Textile, flour milling, cement, leather, oil mills, and sugar are the main industries of the region. Blue Nile is the largest producer of textiles and sugar in the Sudan because it is also the largest producer of cotton and cane, the two raw materials used in producing textiles and sugar.

Western Sudan region accounts for 9.1% of the industries. The region (especially Kordofan) is known nationally as the biggest center of vegetable oil in the country. Most of the oil mills are located in Kordofan. The Western region produces more than 40% of the country's

Table 8

The Location of Industry in the Sudan 1977

Province	No. of Factories	% of Total	Main Industries
Khartoum	547	66.5	Textiles, Spinning and Weaving
Blue Nile	93	11.4	Sugar, Textiles, Flour Milling, Oil Mills, Cement
Kassala	26	3.2	Food
Northern	34	4.2	Food
Kordofan	57	7	Oil Mills, Textiles
Darfur	17	2.1	Food
Red Sea	39	4.7	Oil Mills, Flour Milling
Southern Region	8	0.9	Sugar, Textiles, Food Processing, Tobacco, Light Engineering
Total	822	100.0	

Source: A. S. Norconsult, Sudan Feeder Roads Master Plan (inception report), Khartoum, Sudan, 1979.

production of sesame and groundnuts, two of the major raw materials in the edible oil industry. Other important industries found in the region include textiles, food, and a few other handicraft industries such as shoe manufacturing.

The remaining regions, the Red Sea, Kassala, Northern, and the Southern region, have a varied but limited number of industries. Together, the four regions share 10% of industries in the Sudan. The large deposits of gypsum in the Red Sea region facilitated development of the cement industry there. A new cement factory is being set up in the Red Sea region mainly as an export plant with 300,000 tons a year targeted for export out of a 500,000 tons capacity. Eventual capacity of the plant would, however, be increased to one million tons a year. Other important industries in the Red Sea region are oil mills, flour milling, and fertilizers.

The Kassala and the Northern regions are dominated by food industries, mainly canned fruits and vegetables, as well as the cement industry. The annual capacity of the cement factory in the Northern region is 200,000 tons a year but the factory is being expanded to 500,000 tons capacity (119). The Southern region's industry is concentrated in sugar, textile, food processing, tobacco, tea, coffee, and light engineering industries. Most of these industries are located in the Equatoria region, especially the Nzara agro-industrial complex which employs about 2,000 persons.

Exports and Imports

Exports in the Sudan consist almost exclusively of agricultural products with cotton ranking first, groundnuts second, then sesame, gum-arabic, animal feed, and a few other items. Imports mainly include capital goods, transportation equipment, spare parts, textiles, and foodstuffs. The volumes of exports and imports for 1975 and volumes envisaged for the Six-Year Plan period ending in 1983, are shown in Tables 9 and 10, respectively. A dominant feature in the structure of Sudanese imports is that there is ample opportunity for import substitution since a large portion of the imported goods, mainly foodstuffs and light manufactures, could be produced locally. By the end of the 1983 planning period foodstuffs are to be replaced by material and equipment needed for further expansion as the number one Sudanese import.

Summary and Conclusions

The locational pattern and structural characteristics of population, urbanization, and the economy of the Sudan shows that there is an unequal distribution of economic activities that has given rise to a strong regional concentration of activities. Data indicate that there is a growing trend toward a spatially specialized economy in the country. The share of nonagricultural activities, especially industry, is higher in Khartoum than in any other region in the country. Industrial specialization coupled with a high level of urbanization has made the region of Khartoum a major source of industrial production to other

Table 9

Exports Volume for 1975 and Projection for 1982-1983
(000 tons)

Export Items	1975	1982-1983
Cotton	144	257
Groundnuts	206	50
Sesame	57	20
Gum-Arabic	51	60
Sorghum	48	500
Meat	10	45
Animal Feed	160	220
Vegetable Oils	Nil	240
Hides and Skins	6	12
Sugar	Nil	470
Cement	Nil	250
Petroleum Products	300	100
Ores	30	60
Others	Nil	110
Total		2,394

Source: Sudan Ministry of National Planning, Six Year Plan: Transport and Communications Sector, 1977-1983, Khartoum, Sudan, 1978.

Table 10

Imports Volume for 1975 and Projection for 1982-1983
(000 tons)

Import Items	1975	1982-1983
Wheat	130	50
Sugar	132	Nil
Coffee, Tea	27	30
Foodstuff	17	18
Timber/Wood	30	89
Fertilizers	276	496
Insecticides	14	17
Crude Oil	1,140	1,900
Petroleum Products	100	150
Paper	25	30
Textiles	25	5
Jute Sacks	36	40
Glass and Glassware	10	14
Other Chemicals	45	90
Vehicles	40	60
Iron and Steel	40	138
Cement	100	Nil
Machinery	60	80
Miscellaneous	70	90
Total	2,367	3,299

Source: Sudan Ministry of National Planning, Six Year Plan: Transport and Communications Sector, 1977-1983, Khartoum, Sudan, 1978.

regions and a major source of demand for food as well. Within the sphere of industrial activity, regional specialization is prominent in industrial commodities such as textiles in the Blue Nile region, food oil in the Western region, and sugar in the Blue Nile and the Southern regions. The share of food crops such as sorghum is found to be higher in the Blue Nile and Kassala regions than in any other region in the country. The Western region is specialized in export-oriented crops like groundnuts, sesame, and gum-arabic, whereas the Northern region's economy is dominated by crops like fruit and pulses. Concentration on these cash crops, however, has lead to a food deficit status in both the Western and Northern regions. Similarly, the share of agricultural import-substitute commodities like wheat, rice, sugarcane, coffee, tea, tobacco, and kenaf (a fiber used for making sacks), is shown to be higher in the Southern and the Blue Nile regions than in most of the remaining regions.

In conclusion, the continuous growth in population, agriculture, and industry--transport generating sources--has stimulated regional traffic growth in the Sudan; and the varying rates of growth have resulted in varying traffic intensity among regions (see Table 11). The rise of regional specialization and the concentration of economic production and population has led to some regions being areas of abundance and others being areas of shortages. All are separated by large distances (see Figure 3). These regions of supply and demand or export centers, and their location and the distances involved have induced significant movements of traffic of readily identifiable pattern

Table 11

Estimated Total Traffic Volume by Region in 1979

Region	Traffic in Tons
Northern	1,529,000
Khartoum	2,332,000
Blue Nile	36,375,000
Kassala	13,536,000
Red Sea	657,000
Kordofan	9,166,000
Darfur	7,575,000
Upper Nile	2,733,000
Bahr El Ghazal	2,690,000
Equatoria	3,541,000

Source: Compiled from A. S. Norconsult, Sudan Feeder Roads Master Plan (draft final report), vol. 1, 2 pt. A, B, C, D, Khartoum, Sudan, 1980.

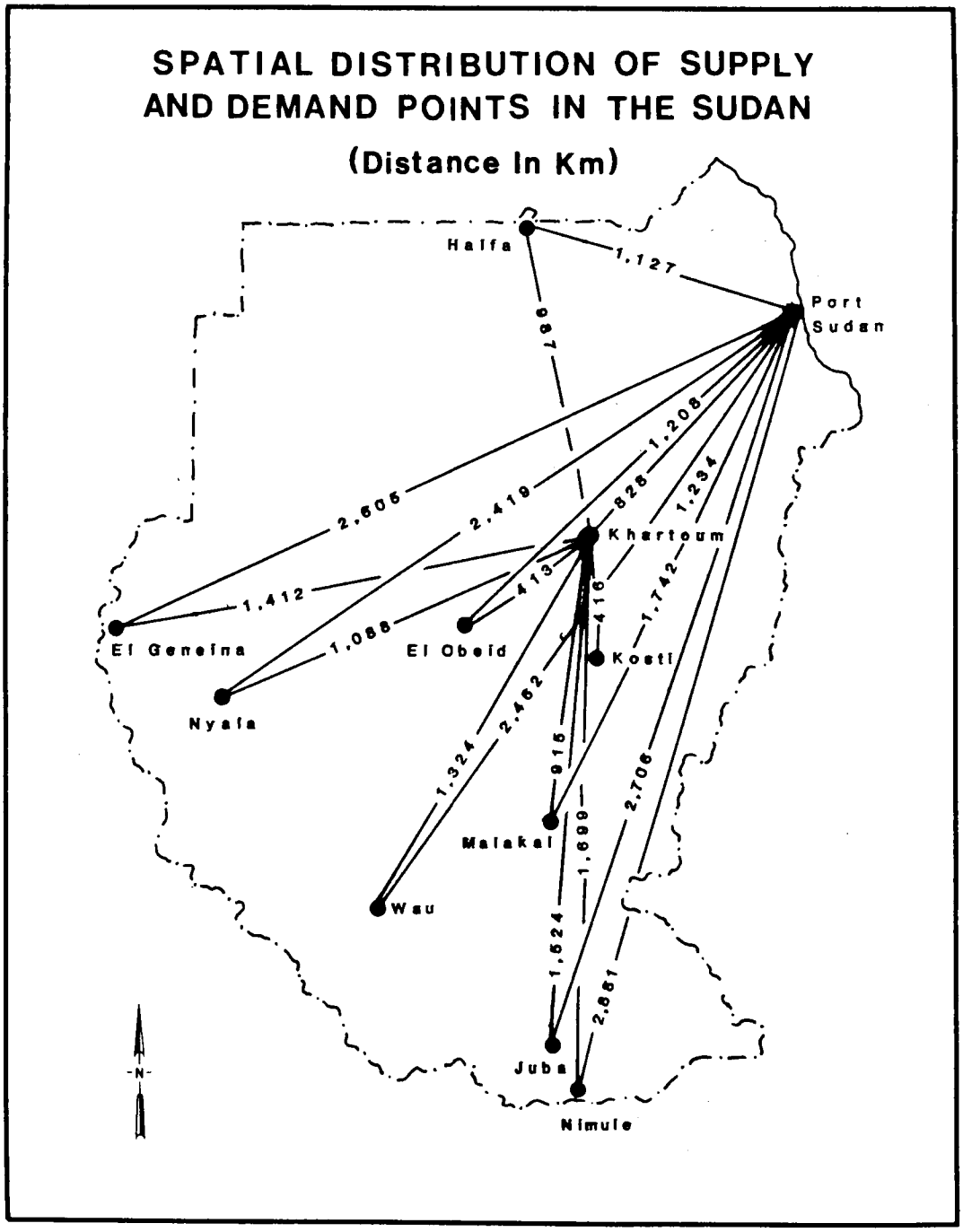


Figure 3. Spatial distribution of supply and demand points in the Sudan.

and character. The extent of this traffic, its characteristics and structural pattern, as well as its growth are analyzed in the following chapter.

CHAPTER IV

ROAD TRAFFIC GROWTH, PATTERN, AND STRUCTURE

Traffic Growth

Since 1970 the share of road transportation in moving both imports and exports traffic and domestic traffic in the Sudan has expanded rapidly. The sharp increase in the use of roads in the Sudan can be shown by examining the main indices of traffic growth--the number of vehicles licensed, motor fuel consumption, and traffic counts.

Table 12 shows the number of licensed motor vehicles (cars, buses, and trucks) on roads in the Sudan. The total number of vehicles increased on the average by more than 8% per annum between 1960 and 1978. This rate of increase varies by mode. There was, for example, an 88% increase in the number of buses and trucks between 1969 and 1974. The number of trucks and buses had been increasing at an annual rate of 14% during the Extended Five-Year Plan period (1970-1977). The number of trucks alone jumped from 11,000 in 1970 to 31,000 in 1977, (an annual increase of 18%) whereas buses increased during the same period by more than 65%. Also available statistics show that the size of trucks has increased. In 1970 the truck fleet was predominantly composed of those with less than 6 tons net capacity whereas in 1975 there were increased numbers of truck-trailers with capacity of 25-30 net tons (92). As a result of this increase in number and average size of trucks, total carrying capacity of trucks jumped from 47,000 tons in 1972 to 161,000 tons in 1976, a 71% increase.

Table 12

Growth of Motor Vehicles in the Sudan

Year	Passenger Cars	Buses	Trucks	Total (Passenger Cars + Buses + Trucks + Others)
1958	11,000	400	12,600	--
1960	15,199	604	13,116	--
1961	15,468	1,214	15,468	--
1962	16,781	1,004	14,767	--
1963	18,594	1,393	16,839	--
1964	18,967	1,498	17,413	--
1965	23,062	1,614	19,940	--
1966	23,704	1,804	17,650	--
1967	25,117	1,949	16,076	--
1968	25,424	2,363	11,929	49,881
1969	27,013	2,081	11,753	52,480
1970	25,387	2,003	10,817	49,484
1971	28,026	2,015	12,677	52,797
1972	29,407	2,782	15,813	59,450
1973	31,663	3,084	20,088	68,119
1974	38,143	3,137	22,908	79,079
1975	40,488	3,274	30,462	91,597
1976	44,631	3,952	29,465	96,928
1977	52,950	5,771	31,597	110,858

Source: Sudan Ministry of National Planning, Transport Statistical Bulletin, Khartoum, Sudan, 1977.

Fuel consumption by road vehicles, under occasional supply constraints, went up (Figure 4). In 1975 fuel consumption was more than 110% higher than in 1963. Available indicators suggest still higher consumption rates in the coming years (96). During the Extended Five-Year Plan (1970-1977) gas and oil consumption by road vehicles increased at a rate of 6.2% annually.

The relative development of road traffic is also illustrated by figures on total intercity passenger and freight traffic in the whole country. In 1969/1970 the intercity traffic volume (interval trade) totalled 3.7 billion ton-km. and 4.69 billion passenger-km., with the following share to each transport mode:

Rail	2.70 billion ton-km.	1.01 billion passenger-km.
Road	0.92 billion ton-km.	3.48 billion passenger-km.
Air	not significant	0.13 billion passenger-km.
Total	3.70 billion ton-km.	4.69 billion passenger-km.

By 1975 total freight and passenger traffic reached 4.828 billion ton-km. and 7.31 billion passenger-km., respectively, with the following share moved by each mode:

Rail	2.274 billion ton-km.	1.102 billion passenger-km.
Road	2.464 billion ton-km.	5.840 billion passenger-km.
River	0.082 billion ton-km.	0.088 billion passenger-km.
Air	0.008 billion ton-km.	0.286 billion passenger-km.

In a span of only five years the freight and passenger traffic moved by road grew by 167% and 68%, respectively, which was more than the Five-Year Plan had projected (97). The road traffic is expected to

TRENDS IN CONSUMPTION OF FUEL BY VEHICLES ON ROADS IN THE SUDAN

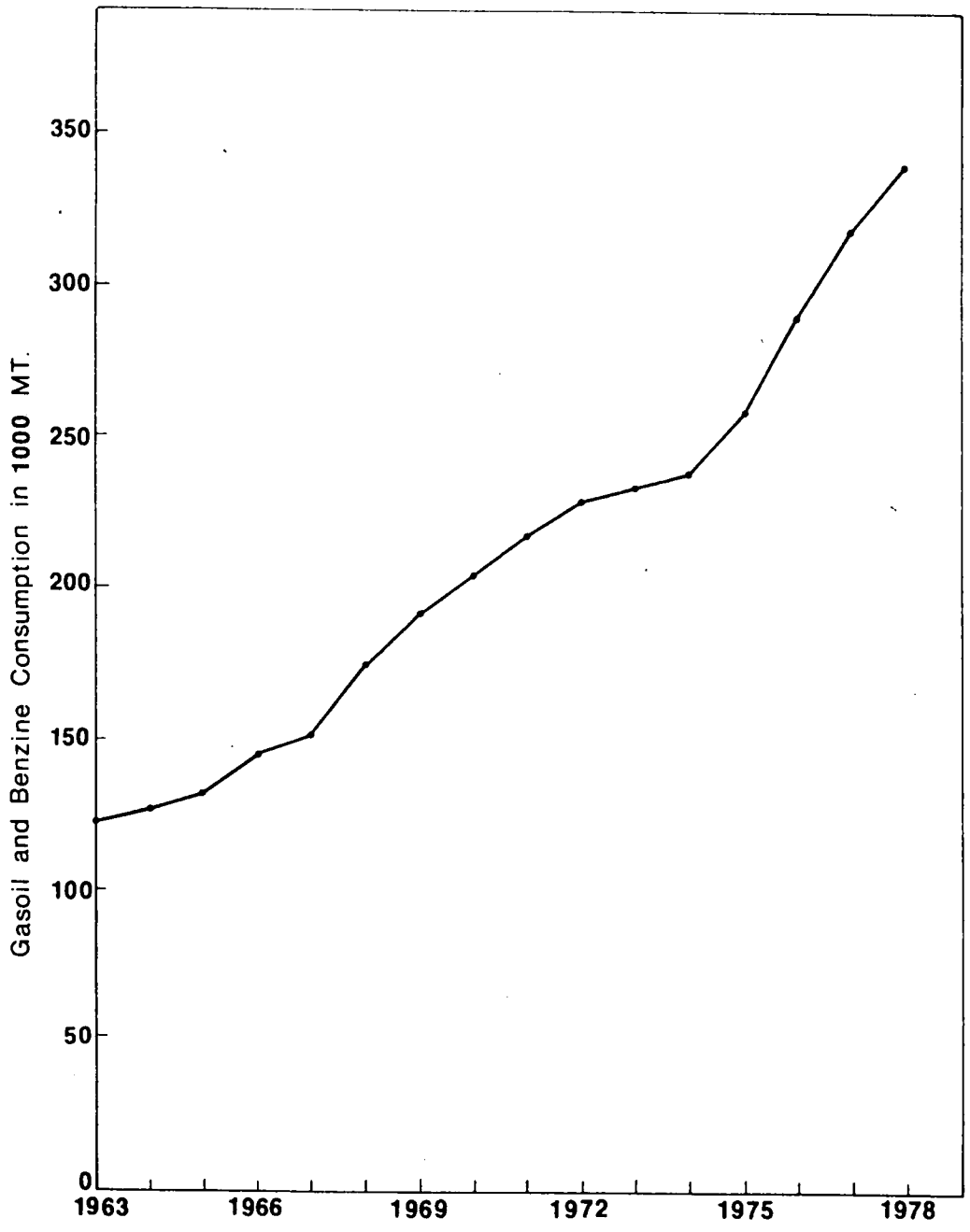


Figure 4. Trends in consumption of fuel by vehicles on roads in the Sudan.

reach 4.98 billion ton-km. and 10.7 billion passenger-km. by the end of the current (1977-1983) Six-Year Plan; a 31% and 78% increase in freight and passenger traffic respectively over traffic in the base year of 1977.

Traffic Pattern and Structure

Any attempt to provide comprehensive coverage of all interregional transactions and establish a clear and consistent pattern of traffic flows for all regions in the Sudan is difficult because of the incompleteness and irregularities in the published traffic survey statistics, particularly origin-destination surveys. In the present study, data is melded together from various available sources to describe the existing pattern of traffic flow and an effort is made to quantify these flows where possible. The road traffic pattern is described on a regional basis with an emphasis on the major roads connecting the regions. Traffic in the Sudan is moved over several defined and undefined roads and tracks connecting pairs of regions. Figures presented here do not, therefore, represent all traffic on roads among regions. In the analysis, consideration is given only to traffic on those roads for which some data are available; these are usually the most important intercity roads in the country.

The Traffic Pattern in the Northeast Region

Khartoum constitutes the pivot of the Sudan in terms of traffic exchange because of its proximity to various productive parts of the

country. Roads fan out of the region in all directions linking the region to many others in the country.

Most of the traffic emanating from, or destined for, Khartoum follows the roads connecting the region with the Blue Nile region, namely, the Khartoum-Medani and Khartoum-Kosti roads. On the average, 3,111 vehicles (46% trucks, 36% passenger cars and buses, 18% miscellaneous) moved along the Khartoum-Medani road daily in 1978, carrying 25-30 thousand tons of freight and about 50,000 passengers between Khartoum and the Blue Nile region. Of this total tonnage 79% entered Khartoum from the Blue Nile while 20% left Khartoum to the Blue Nile region. On the average, 77% of the trucks which went out of Khartoum were found either empty or half-full whereas inflow into the region consisted largely of overfull and full trucks. Buses were usually full in both directions.

A large number of different commodities including machinery and spare parts, food and drinks, household items, fruits and vegetables, sugar, and sand and gravel were trucked from Khartoum to the Blue Nile region. Cotton seed, coal, sorghum, groundnuts, machinery and spare parts, drinks and food, fruits and vegetables, sugar, and household effects were moved in the opposite direction along the Khartoum-Medani road.

A large proportion of traffic between Khartoum and the Blue Nile region is also carried out along the Khartoum-Kosti road. In 1978, about 800 vehicles per week, on the average, moved between the two regions carrying various consumer products and materials such as sugar,

tea, household items, machine and spare parts as well as passengers to the Blue Nile region. Lint cotton, sorghum, groundnuts, sesame, and fish were trucked in the opposite direction to Khartoum.

Traffic between the Khartoum and Kassala regions is basically channelled through the Khartoum-Kassala road. In 1978, total average daily traffic was 2,115 vehicles of which 78% were trucks engaged in carrying freight and the rest were passenger vehicles. Total tonnage moved daily between the two regions was approximately 12,150 tons of which two-thirds moved into Khartoum and one-third out of Khartoum. Most of the trucks moving into the Khartoum region were fully loaded whereas 70% of the trucks moving out of Khartoum were either empty or half full. The inflow and outflow of bus passenger traffic was fairly balanced, usually on buses loaded to capacity.

Commodities that were entering the Khartoum region included sugar, sorghum, cotton, coal, machinery and spare parts, food and drinks, gravel and sand, fruits and vegetables, while those leaving Khartoum included cotton seed, food and drinks, groundnuts, and fruits and vegetables.

Traffic between Khartoum and the Northern region moves mainly along the Khartoum-Atbara and the Khartoum-Dongola roads. No recent information is available about the traffic on these roads, but according to the Adar study of 1974, about 200 tons were moved daily along the Khartoum-Dongola in both directions (103, vol. 3). Considerable passenger movement exists between the Khartoum and the Northern regions but precise figures are not available. The northbound road traffic consisted of

high value goods especially spare parts, sugar, tea, coffee, and other food crops such as sorghum. The southbound traffic was made up of agricultural commodities such as dates, onions, and pulses (103, vol. 3).

Port Sudan handles the majority of import and export traffic in the Sudan. In 1978 about 742 trucks carrying at least 5,000 tons, moved in and out of the port daily. This tonnage was equally divided between in- and out-flow. Trucks leaving and/or entering Port Sudan were full and overfull. About 86-88% of the total vehicles originating in or destined for Port Sudan moved between Port Sudan and the Khartoum region while only 11% travelled between Port Sudan and various other regions of the Sudan, mainly the Blue Nile and Kassala regions. Estimated average haul of trucks was 927 km. (100).

Traffic between Port Sudan and the region of Khartoum is moved through three major road arteries: the Khartoum-Medani-Gedaref-Kassala-Port Sudan, Khartoum-Kassala-Port Sudan, and Khartoum-Atbara-Port Sudan roads, with 39%, 30%, and 28% of total traffic between the two regions, shared by each road, respectively. The remaining proportion of traffic between the regions (3%) is moved on undefined routes (94).

In 1978, a large variety of goods were moved from Port Sudan to Khartoum of which the most important were cement, equipment, raw iron, cars, drugs, textile and cloth, jute, tea, timber, and paper. The types of goods moved from Port Sudan to the Blue Nile and Kassala regions are almost the same as those destined for Khartoum, with machines, spare parts, and cement dominant. Commodities which were moved from the

Khartoum region to Port Sudan included oil cakes, stones and sand, cotton, groundnuts, gum-arabic, sorghum, sugar, watermelon seeds, and sesame. Most of these commodities moved out of Khartoum destined for Port Sudan actually originated in the Western region. Cotton and cotton seeds were moved from the Blue Nile region to Port Sudan, and sorghum, sesame, and cotton went to Port Sudan from the Kassala region.

Traffic interaction between the Blue Nile and Kassala regions is more dominated by passenger movement than by freight. For example, of the total daily average traffic, estimated at 1,659 vehicles in 1978, more than 50% were buses and passenger cars whereas only 33% were commercial trucks. Most of the traffic moves on the Medani-Gedaref road. In 1978, over 3,780 tons were moved daily between the two regions. No exact figures are available to identify the volume of traffic moving in each direction; but according to information available in recent traffic counts, about 83% of the trucks travelling in the direction of the Blue Nile region were found full while those moving in the direction of the Kassala region were recorded full in 54% of the cases (94). It could, therefore, be deduced that the largest proportion of the traffic moves from the Kassala to the Blue Nile region rather than in the opposite direction. Most of the traffic from the Kassala region to the Blue Nile region is composed of sorghum, sugar, and wheat, which would be finally destined for the Khartoum, Western, and Southern regions.

The Traffic Pattern in the Western Sudan Region

The Western region has most of its traffic exchange with the Khartoum and Blue Nile regions. It has also a fair amount of traffic activity with the Southern region, but has almost no traffic with the rest of the country.

The actual daily volume of traffic between the Western region and the Northeastern region (particularly the Khartoum and Blue Nile regions) was estimated at 402 vehicles, moving both directions (121). Of this total, 286 trucks operated between the Western region and the Khartoum region alone. This represents, however, an aggregated figure of the traffic which came from various origins (small towns) in the Western region. It does not therefore represent traffic along one particular route. Traffic from the Western region, in fact, moves on various defined and undefined roads and tracks the bulk of which link in Kosti or Khartoum. The traffic to Khartoum is, therefore, moved directly, along the El Obied-Khartoum road for example, or by way of the Blue Nile region along the Kosti-Khartoum road.

It is estimated that a total of 190,000 tons of freight move annually between the Western and the Northeast regions (121). Most of this freight is composed of unprocessed cereals, consumer goods, mineral oil, and building and construction material. From the Western region, gum-arabic, sesame, food oil, beans, vegetables and fruits, animal food (oil cake), and a small amount of manufactured goods, are sent to the Northeast. The Western region receives a variety of commodities which

include sorghum, fruits, vegetables, mineral oil, and other consumer goods.

Passenger transportation constitutes an important component of traffic between the Western region and the Northeastern region (especially the Blue Nile region). According to available traffic counts, about 3,752 persons move daily between the two regions (121). Out of this total only 800 persons move between the Western region and Khartoum; all of the rest are transported to the Blue Nile region. The seasonal labor movement accounts for a large proportion of the total passenger movement, amounting to 875 persons daily. These workers travel by trucks to work as cotton pickers on the Blue Nile region agricultural schemes. Transportation of these seasonal cotton pickers has almost doubled the road traffic volume by adding, on average, 243 trucks daily to the already existing daily traffic between the Western and Blue Nile regions.

The Traffic Pattern in the Southern Region

Road traffic between the Southern region and other parts of the country is at present fairly low. This is because of the remoteness of the region from the main centers of production and the port and because of operational limitations attributed to road conditions. Most of the roads in the region are earthen (unpaved). Climatic conditions affect such roads adversely. The Southern region, nonetheless, has some trade exchange with neighboring countries to the south, namely, Uganda and Kenya, but this trade is of very limited scope. For example, commodities

like cement and a few other consumer goods are moved by road from these countries to Juba. Such inter-country movements do not lie within the scope of interregional road network under study.

The Southern region has virtually all its traffic exchange with the Khartoum, Blue Nile, and the Western regions. An estimated total of 167 vehicles, on daily average, move between Khartoum and the Southern region, carrying 377 tons of agricultural and consumer goods and 1,122 passengers. According to the Adar study of 1974, an estimate of 80 trucks carrying 500 tons daily from the Upper Nile region enter Kosti (in the Blue Nile region) through the Malakal-Kosti road. These trucks carry unginned cotton to the gins in Kosti and carry back supplies for local consumption such as sugar, tea, textiles, as well as machinery and spare parts.

It is estimated that 200 tons of goods are transferred daily between the Bahr El Ghazal region in the south and the Kordofan region in the west. This traffic is carried over the Wau-El Nahud road. Another 300 tons per day move between the Bahr El Ghazal and Darfur regions along the Nyala-Wau road (103, vol 3). Most of the shipments to the Southern region consist of high value consumer goods (some of which emanate from the Khartoum region), whereas commodities moving out of the region consist mostly of hides, cotton, and a few other agricultural products.

Traffic among the three southern regions, Equatoria, Upper Nile, and Bahr El Ghazal, is extremely low. For example, 10-15 commercial vehicles move daily between the Equatoria and Bahr El Ghazal regions on

the Juba-Wau road. Commodities moved include meat, fish, cereal, fruits, and some vegetables. Also 133 passengers leave the Bahr El Ghazal region (from Wau) to the Equatoria region (to Juba) daily and 146 arrive in the Bahr El Ghazal region from Equatoria (114). No information is available on the volume of road traffic between the Upper Nile and Bahr El Ghazal or between Upper Nile and Equatoria regions, but generally these traffic flows are insignificant because of the swampy barriers in the Upper Nile region.

Seasonality and Road Transportation

The pattern of traffic flow in the Sudan described above is sometimes influenced by seasonality of rainfall and soil type. Generally in Central and Eastern Sudan, traffic along earth tracks comes to a halt during the rainy season, July-October. Because of prevailing clay and clay-silt soils in these parts of the country, roads become impassable. In the Western region, where sand dominates, the effect of rainfall on traffic is less than in the Central or Eastern Sudan. The issue of seasonality and soil type and their effect is further examined in the following chapter when link characteristics are discussed.

The movement of goods sometimes shifts from route to route depending on rainfall and type of soil traversed. Figure 5 is based on an origin-destination traffic count conducted in 1976 and it shows traffic flow between El Obied and Om Ruaba, towns in the Western region. The figure indicates that in the dry season the southern road (El Obied-Rahad-Um Ruaba) was utilized most heavily. On the other hand, during

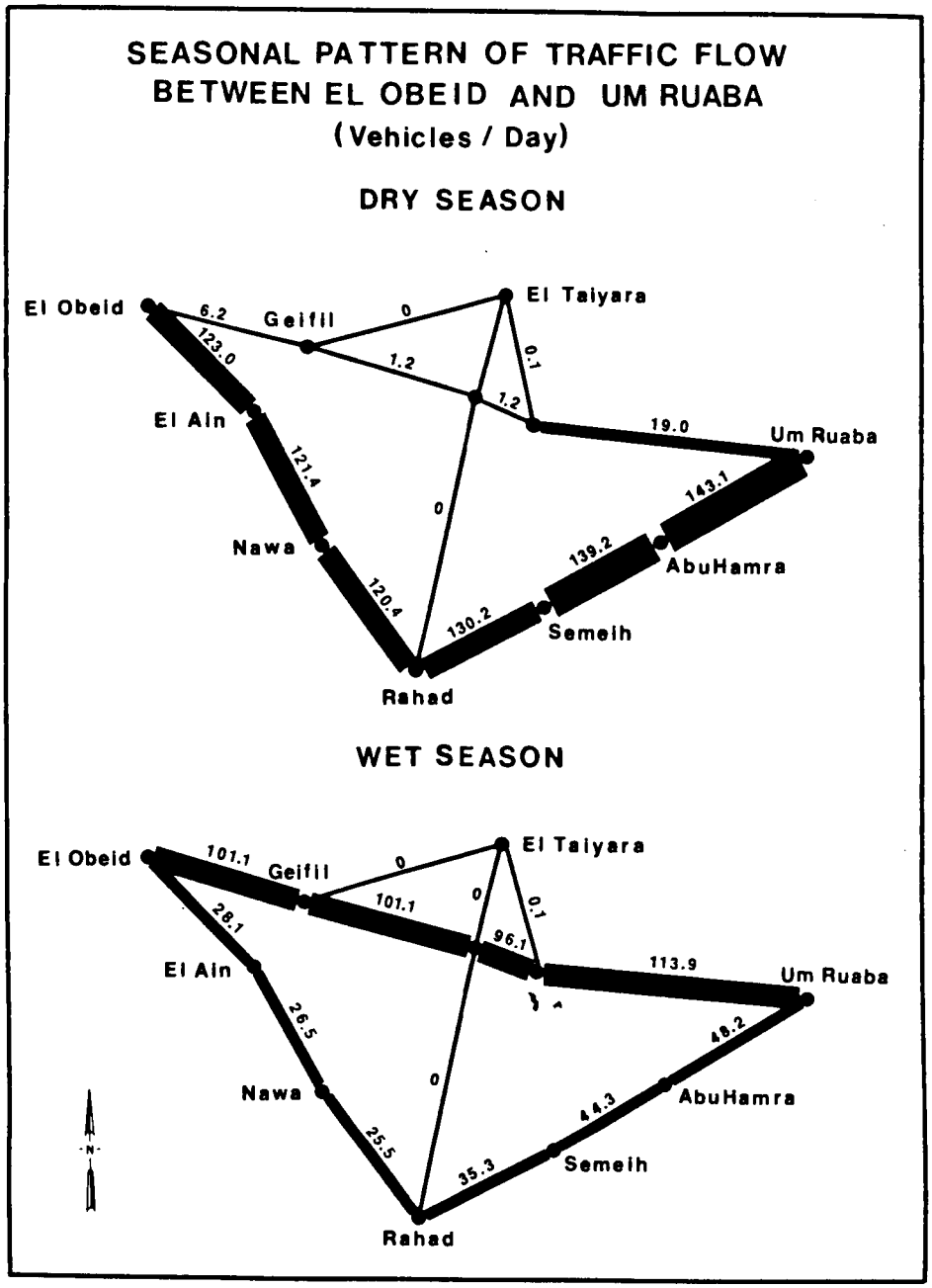


Figure 5. Seasonal pattern of traffic flow between El Obied and Um Ruaba.

Source: Japan International Agency, Feasibility and Preliminary Engineering Study of Road Project (El Obied-Um Ruaba), Khartoum, Sudan, 1978.

the rainy season, i.e., June-October, the traffic was diverted to the northern road (Obied-Shamgatta-Um Ruaba). The main reason for this shift is that during the rainy season the southern road becomes muddy because of the silty soil, and traffic is interrupted for quite long periods, while the northern road traverses sandy soils (Qos) which are permeable and drain water rapidly. Similarly, traffic shifts have been noted from the Khartoum-Kosti-El Obied road which is a clay soil road type, to the Khartoum-El Obied road which traverses sandy soil (Figure 6).

General Evaluation and Conclusions

The foregoing discussion provides an approximate description of road traffic flows as they exist in the Sudan. The pattern of flows is generally simple but in some specific cases it is complex because of the indirect nature of the through traffic.

The traffic flow in the Sudan has a defined pattern, at least in the case of Khartoum and Port Sudan as well as the Western region, which act as either dominant sources of traffic origin and/or destination. In general, the bulk of freight traffic moves to Khartoum and Port Sudan. The Khartoum and Blue Nile regions attract the largest flow of traffic. Productive regions are quite spatially separated and the movement of some commodities, therefore, involves long distance hauls. The current Six-Year Plan placed special emphasis on the dispersion of present economic activity to the less-developed regions. This policy should aid in reducing the present imbalances of traffic flow in different directions, and will decrease the relative trucking distances of some

SEASONAL PATTERN OF TRAFFIC FLOW BETWEEN KHARTOUM AND EL OBIED

(Tons / Day)

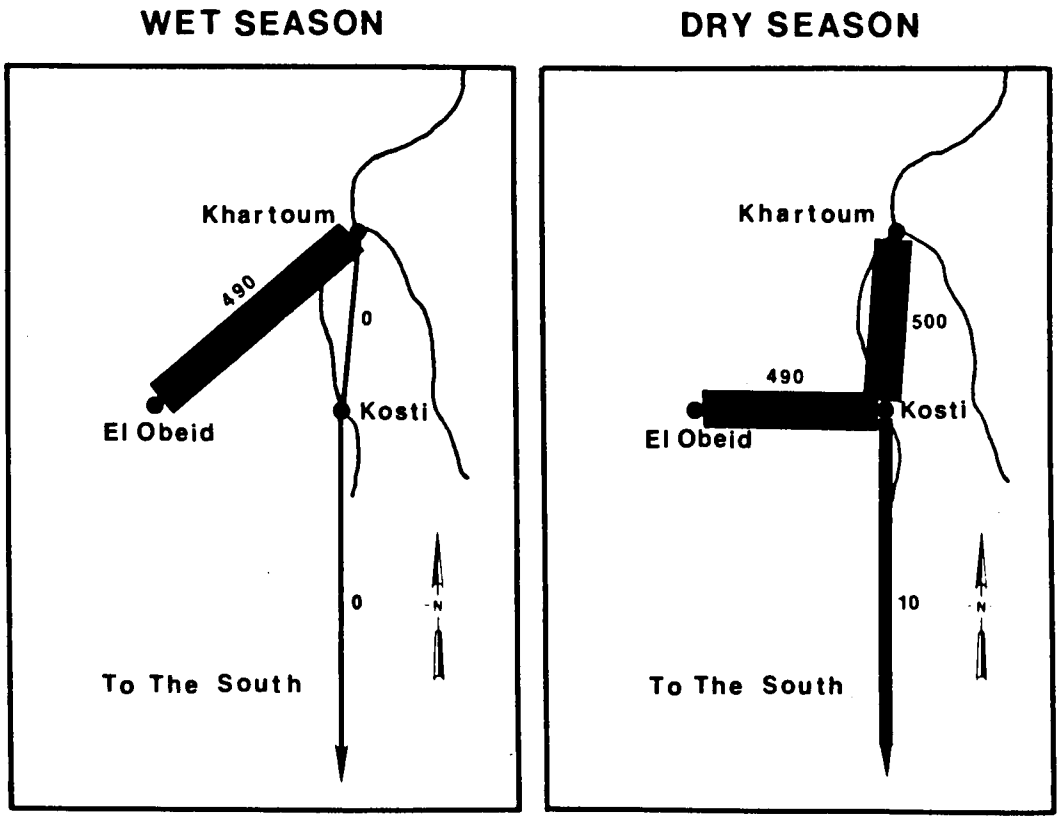


Figure 6. Seasonal pattern of traffic flow between Khartoum and El Obied.

Source: Japan International Agency, Feasibility and Preliminary Engineering Study of Road Project (El Obied-Om Ruaba), Khartoum, Sudan, 1978.

commodities, such as sugar, and increase the average haul of some others, such as agricultural machinery needed for investment. It may, however, result in the increase of total volume of freight traffic in the Sudan as well.

For most of the regions, Khartoum assumes a distributive and redistributive function. The products moved into and out of Khartoum are, in most cases, the same. Indeed, the distribution of some commodities among the various regions in the Sudan is controlled by the government. For example, sugar distribution is a direct responsibility of the public authorities (centered in Khartoum) who receive the imported and locally produced sugar and then allocate quotas to the regions. In this case all sugar supplies are moved from Port Sudan, Blue Nile, and Kassala, to Khartoum. Then sugar is trucked from Khartoum to other regions including the regions of production themselves. With the expected increase in volume of sugar production and number of supply regions, however, sugar movement from production site to a central place may be eliminated and sugar supplies could be provided from regions of production directly to regions of consumption. Substantial savings in distance and cost would be realized by so doing. Khartoum is the dominant source of origin and destination for commodities of the Southern region. This is contrary to what might be expected. The Blue Nile region is, for example, nearer to the Southern region than Khartoum, and has a surplus that is quite enough to meet all the Southern region needs in most of the transported commodities. Also the Blue Nile region is closer to Port Sudan, the major source of

imported consumer goods needed in the Southern region. It would seem, therefore, quite sensible for the Blue Nile region to act as a distributive and redistributive center of goods destined to and from the Southern region rather than Khartoum.

Import-export traffic constitutes a large proportion of road vehicle traffic. Over the last few years the export pattern has remained fairly stable with cotton, groundnuts, sesame, sorghum, gum-arabic, and edible oil dominating. Also a very large number of commodities are being imported (e.g., sugar, cement, jute sacks, textiles, machinery). Almost all types of commodities move by road. Import and export commodities dominate the structure of road traffic movement at present. Development programs envisaged in the Six-Year Plan aim at expansion of production and diversification of crops for export and expanding import-substitute products. One might, therefore, expect significant changes to occur in the pattern and volume of exports and imports. These changes are prominent for items like cement, sugar, wheat, and textiles as well as for some export products (see Tables 9 and 10, pp. 63 and 64). This change in volume and type of commodity will, therefore, be reflected in the structure, volumes, and pattern of freight traffic movement in the country.

The increasing use of motor vehicles in the movement of bulky goods over short, medium, and long distance, is an indication of the successful experimentation with use of these vehicles for long haul shipments of bulky commodities. Road transportation in the Sudan is not, therefore, only suitable for the movement of high value goods over short

distances. The importance of road transportation given both its reliability and speed seems destined to increase in the Sudan. The commodities moved, which are largely agricultural, are susceptible to damage and deterioration due to time, weather, and handling.

Trucking operations in the Sudan cannot be carried out throughout the year. Most of the regions are at present linked by tracks or gravel roads. Long distance road traffic is still inhibited in some areas by the poor conditions that cause excessively high operating costs. Traffic is normally lowest during the rainy season when trucks often completely stop their operations. On the average, trucks operate only 9 months a year.

It has been shown that trucks going out of Khartoum often have very light loads to carry but on their back-haul they were often overloaded. Trucks entering or leaving Port Sudan were, however, usually overloaded in both directions. Such inefficiencies should be eliminated if road transportation is to realize its full potential in the Sudan.

The dispersion of economic activity among various regions should lessen the load disparities in the movement of trucks. Expansion and improvement of modern roads will allow all year round truck operations; thereby increasing the average annual kilometers per truck, the utilization rate of trucks, and reducing their operating and maintenance costs. The final result of all these changes should, therefore, be an increase in the total volume of freight traffic.

The export-import orientation of road traffic combined with few major producing centers (e.g., the Blue Nile region) and few centers

consuming imported goods translates into strong concentration points of road transportation demand. Increased demands for improved road transportation facilities over certain road links (e.g., Khartoum-Medani and Khartoum-Port Sudan) form the basis for the growth of the road network in the country.

CHAPTER V

ROAD NETWORK GROWTH, PATTERN, AND CHARACTERISTICS

Growth and Pattern

A common theme throughout the evolution of the road transportation system in the Sudan has been the steady rise in the importance of road traffic which first compliments the railroads, then competes with it, and finally overwhelms it. Historically, the spatial pattern of growth of the road network was unevenly distributed over both time and space. Three major stages in the growth of the road system can be distinguished: (1) the pre-Independence period, (2) the 1956-1973 period, and (3) the post-1973 period. Each of these stages will be differentiated by the main variables affecting network expansion.

The Pre-Independence Period

During the precolonial period, i.e., before the 19th century, caravans constituted the major road transport services in the Sudan. The development of these routes was associated with movements of Arab nomads before the 16th century. The caravan routes traversed long distances and in some cases crossed the whole country. One major caravan route ran from the northern border at Asyot in Egypt across Central Sudan and then westward to the western region. This route was of particular importance because of the cultural contacts established with Egypt. It was also important to internal trade among market towns. This trade developed along the route at the Nile River crossings such as

Damar, Dongola, and Berber in Northern Sudan, and Omdurman and Sennar in Central Sudan. Another caravan route ran from Gineina in the western border region of the Sudan across the central plain to the eastern part of the country. This route was associated with the development of Swakin as a port on the Red Sea, providing a link of the country with some Asian and African countries. The route acquired overriding importance as the main axis of pilgrim movements from west to east. The two caravan routes retained supreme importance especially in long distance traffic movements until the coming of modern steamers and railroad transportation in 1896, the beginning of colonial rule.

The importance of motor vehicles began to be felt in the late 1920's in many parts of the country. In the Blue Nile, Khartoum, and Kassala regions, where commercial agriculture and population concentrations had already developed, motor transportation was able to compete for the carriage of passengers and for the traffic in high value goods such as cotton and cotton seeds. As a result of this traffic, short distance earth tracks started to be developed, replacing animal and footpaths as the main rail feeders. The use of trucks made many of the caravan routes unnecessary.

In Northern Sudan, rail-steamer service began to attract considerable traffic in the region. But because of the increase in transport demand and the slow rail-steamer service between Khartoum and the Northern region, goods were apt to be delayed. Motor vehicle transport was, therefore, developed as a quick and reliable alternative to the slower steamer. Three major earthen routes were developed among

the rail-steamer terminals as well as among intermediate points. The first and most important route connects the active markets of Omdurman and Debba. Although this route did not exactly coincide with the caravan route, the traffic along it replaced the regular caravan traffic in the region. Since 1948 trucks have made regular use of this route. The second route connects Damar, capital of the Northern region, with Merewe and from there the route proceeds to Karima. This route gained importance in 1948 after a regular river ferry began to operate at Atbara primarily for the use of the new cement works. Despite its limited use for economic purposes, however, the route serves administrative needs in the region. The third route connects Karima with Dongola across the desert north of the Nile valley (74).

As soon as roads started to compete with the government-operated railroads in the interregional movement of cash crops for export and the distribution of consumer imports, the government curtailed that competition. Legislation was passed in 1934 prohibiting the carriage of goods by trucks between Port Sudan and Kassala, Port Sudan and Atbara and Atbara and Wadi Halfa, except in emergencies and/or by permit from the Governor of the province concerned (113, 82). It was clear from the beginning that the government wanted to grant the railroads complete monopoly over other forms of transport, especially roads. With this legislation, the basic concept of road transportation policy was for the first time clearly outlined. The policy aimed to avoid building roads over long distances parallel to any railway line, to construct roads in regions that were not served by railway, and to build low cost roads.

By implementing this policy, the government discouraged the growth of the road transportation sector during the whole colonial period. The government felt that there was no need to build expensive paved roads since trucks could travel on earth tracks, at least during the dry season. The railroad was felt to be the decisive instrument for the development of the country whereas road transportation should play a subsidiary role as a feeder. During the colonial period, therefore, transportation on most of the road systems throughout the country consisted mainly of tracks, portages, or caravans either as feeders to the railways or completely independent of them. Only a few major long distance roads were constructed in the country. Those roads were in the underdeveloped Southern region in Bahr El Ghazal and Equatoria Provinces where rail service was nonexistent.

In the Southern region, where the issue of competition between rail and road transportation did not arise, low cost road construction (mainly gravel roads) was undertaken. The process of building these low cost roads was reinforced by availability of laterite in the Equatoria and Bahr El Ghazal Provinces which is suitable for building all weather roads at low costs. Further, the dry season was so short that dry weather tracks of earth were impractical. The major factor which provided the impetus for road construction in these provinces was, however, political rather than economic.

In their attempt to ensure political control of the Southern region, colonizers shifted the site of their regional capital in the Southern region several times. In the Equatoria Province, for example,

Mongala, Lado, Gondokro, Rejaf, and Dufile, have all been designated as regional capitals at different times. This shift facilitated construction of the Juba-Nimuli road (175 km.) in 1928. Its purpose was to link Juba, which has been the province's capital since 1930, with Uganda. Juba lies approximately at the head of navigation of the Bahr El Jebel and it is the terminus of the river steamers from Khartoum. Linking Juba with Uganda conformed with the prevailing tendencies for a general orientation of the southern part of the Sudan in the direction of Uganda, Kenya, and Tanganyika, the British High Commission Territories. Such a tendency was understandable when one considers the substantial distances between Juba and Khartoum (1,524 km.) or Juba and Port Sudan (2,352 km.) and the low quality service of the steamers serving the southern provinces.*

The choice of Juba as a regional capital in the Southern region represented a compromise between the needs of east-west road communication, which call for an easy approach to the river free from flooding, and the necessity to maintain river communication between the Equatoria region and the rest of the Sudan. The east-west communication was needed to provide access to the main towns so that daily administrative functions of the resident counsellors such as revenue collection and peace maintenance operations could be carried out. The Juba-Torit-Kapoita road (314 km) was, therefore, constructed in 1936, and was

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*The distance between Juba and Gulu (a town in Uganda which lies at a junction of paved roads connecting most centers in Uganda, Kenya, and Tanzania) is approximately 250 km.; and the distance between Juba and Nairobi is 1,147 km.

extended by 1939 to Wau, the regional capital of Bahr El Ghazal. The Juba-Yei, Juba-Aba (213 km.), Juba-Rumbeek-Raja (510 km.) roads were constructed to link the provincial capital with district capitals. In Bahr El Ghazal gravel roads were also built to provide access between various administrative towns. The most important roads built in the province are the Wau-Meshra (109 km.), Wau-Aweil (93 km.), Wau-Raja-Said Bandas (280 km.), and Wau-Yambio (278 km.). By 1939 the two provinces, Equatoria and Bahr El Ghazal, maintained more than 7,000 km. of gravel roads connecting provincial capitals to each other and each capital with its respective district towns.

Unlike the Equatoria and Bahr El Ghazal regions, the absence of laterite and existence of vast areas of swamps made it difficult and expensive to build proper roads in the Upper Nile region, unless they were placed on embankments. There was, therefore, a minimal expenditure on roads in the Upper Nile region compared to the other two regions in Southern Sudan. Such building as did take place was only enough to provide dry-weather tracks such as the Renk-Melut road and the Kaka-Tonga road. In 1932 about 1,171 km. of road in the province were cleared and graded. This grading, however, does not necessarily imply proper embankments were constructed but rather, only smoothing out the surface soil. Figure 7 shows all roads constructed in the Southern region as well as a few other earth roads and tracks developed in other areas of the Sudan during the pre-Independence period.

During the colonial period capital expenditures were allocated on a purely ad hoc basis. The initiation of development projects was left

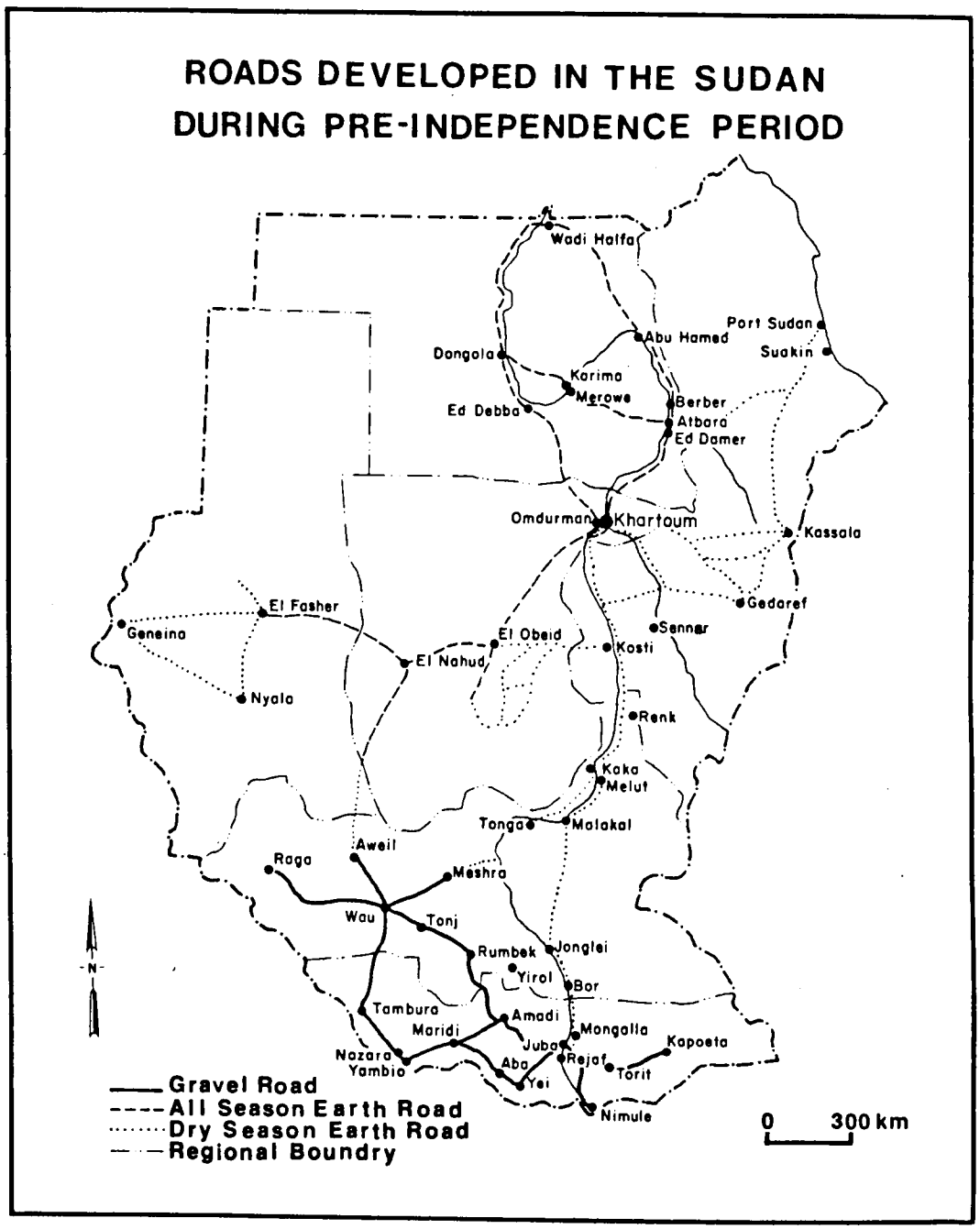


Figure 7. Roads developed in the Sudan during pre-Independence period.

almost entirely to the heads of departments and the provincial administrators. The projects were submitted to the Department of Finance for its opinion, and depending on the size and importance of the projects, decisions on their worthiness were made by either the Secretary of Finance or the Governor General in consultation with his council. The whole period was distinguished by the absence of any special committee or body concerned primarily with development entrusted with scrutinizing projects, investigating their feasibility or determining project priorities. Projects submitted by different departments were studied by officials as part of their day-to-day work. There was no separate budget for development expenditure as distinct from current expenditures. Such conditions of uncoordinated planning structure and practice influenced road development by limiting road expansion and reinforced an unbalanced spatial growth of road transport that persisted a long time. As long as road development was treated as an extra problem on the shoulders of already overburdened provincial governors or government departments, it was never accorded the degree of concentrated effort needed for success, at least in bringing about balanced development of the road system over the whole country. Table 13 illustrates the lack of investment in roads throughout the country during part of the colonial period. The table illustrates the national government expenditure for road maintenance costs compared to the total national expenditure. The maintenance costs were virtually the total road expenditure for the country since almost no construction had been carried out since 1940.

Table 13

Road Expenditure in the Sudan during Part of the Colonial Period

Year	Expenditure in Roads (in Sudanese Pounds)	Total National Expenditure	Percent of Road Expenditure Out of Total National
1941	7,650	5,047,000	0.15
1943	13,099	5,602,000	0.23
1945	16,785	7,548,000	0.22
1947	22,060	9,435,000	0.23
1949	33,200	13,964,000	0.24
1951-1952	57,000	21,532,000	0.26
1953-1954	121,900	27,611,000	0.46
1955-1956	100,000	NA	
1956-1957	105,000	NA	

Source: M. J. Betz III, "An Analysis of Transportation Costs in the Sudan and an Approach to the Engineering Analysis for Transportation Planning in Developing Countries," Unpublished Ph.D. Dissertation, Northwestern University, Evanston, Illinois, 1961.

To build a road in the colonial period, it was not necessary to consider short and/or long-term effects of that investment nor was it necessary to account for the economic needs of opening up productive regions. Security and administrative reasons were sufficient justification for road building projects. Lack of proper road planning was a major reason for the inconsistent spatial pattern of commercialization within the economy, the level of economic development, and road development in the country during the colonial period. Areas which developed far above average like the Blue Nile and Kassala cotton areas, possessed no modern road mileage (at least gravel) or a mileage much smaller than their expected proportionate share. On the other hand, areas which were economically poor and backward such as the Equatoria and Bahr El Ghazal regions possessed a road mileage considerably greater than their state of development might otherwise indicate. The result of such a pattern of development was excess road transportation capacities in some areas and deficits in others.

1956-1973 Period

The first four years after independence in 1956 represent a period of transition. The uncertainty of financial resources led the government to resort to year-by-year economic planning. Tight financing had restricted road expansion. Most of the road system, therefore, still consisted of the old earth tracks dominating all of the Sudan, save the Southern region where there were gravel roads which remained to be either nominally maintained or so completely neglected that their conditions started to deteriorate.

In 1960, a Ten-Year Development Plan was prepared for the first time as a guideline for the future planned and coordinated development of the country. The plan provided for major development projects that brought about major changes in the country's economy. The completion in the 1960's of Roseries and Khasam Elgirba dams in the Blue Nile and Kassala regions, respectively, permitted intensification of cropping in the Gezira area, development of pump schemes along the Blue and White Nile rivers, intensification of cropping on existing pump schemes, and expansion of sugar cane plantation in the regions. Total annual increase of arable land amounted to 500,000 ha. Modern mechanized farming was introduced in the Nuba Mountains area of the Kordofan region as well as in the Gedaref district in the Kassala region. Crop production, therefore, increased in these regions. In the extreme west, the area around Jebel Merra in the Darfur region was developed. In the southern three regions agricultural plantations were established. With this expansion in agriculture, diversification occurred in commercial and food crops. Similarly, manufacturing industries were established. Examples of such industries are oil mills, fruit canning, the manufacture of milk powder, and paper and cardboard factories.

The development suggested by the Ten-Year Plan was based almost exclusively on agriculture. Investments were regionally concentrated in the Blue Nile, Khartoum, and Kassala regions. These are the regions that had already achieved some advancement in the level of economic development. Accordingly, the relative advantage of these areas over other parts of the country increased by the new developments. Regional

disparities were magnified substantially. Such a pattern of economic development was directly reflected in the pattern of road growth during the period of 1960-1973.

Since the Sudan is primarily an exporter of agricultural products, a large percentage of the output was intended for export. This tendency resulted in a strong agriculture-transportation interdependence. The input-output statistics for 1963 show that 86% of agricultural purchases from other industries were made up of purchases from transportation and distribution (115, vol. 2, part 2). Of transportation and distribution sales to other industries, agriculture comprised 63%. Also the same input-output statistics shows the strength of interdependence between transportation and manufacturing for the same year. Despite the limited development of the manufacturing sector, purchases of the sector from transportation and distribution constituted 44% of its total other industry purchases and 17% of its total output (115, vol. 2, part 2). The importance of manufacturing for transportation appears disproportionately greater than manufacturing's contribution to GDP (which was only 2%) would suggest. This fact suggests that any development emphasis on manufacturing could lead to magnified dependence on transportation as well.

The increasing dependence of economic development on transportation improvement has added strain on the existing transportation system. This strain was further accentuated by other factors related to population changes. Available statistics indicate that the percentage share of total population in the northeast region (Blue Nile, Khartoum, and

Kassala) continuously increased during the period of 1955-1973, whereas the percentage share in northwestern region (Darfur, Kordofan, and Northern), as well as southern three regions declined during the same period. Also, the Blue Nile, Kassala, and Khartoum regions were the three regions among all others where the balance between in- and out-migration was found to be positive during the period of 1964-1966. The Khartoum urban area received the largest net in-migration increase with Kassala region a distant second. The other three regions, Darfur, Kordofan, and Northern, recorded a negative balance, i.e., more emigration than immigration (103, vol 3).

The increases in population movement, agricultural, and industrial activities outlined above, increased transportation demand. Priority was accorded to the expansion of the road system. Areas that possessed the greatest economic advantage (Khartoum, Kassala, and Blue Nile) were given preferential consideration. It was in those developed and expanding regions that a high traffic density on the roads was already apparent and the need for an improvement of existing earth tracks was most urgent. The first bituminous intercity road (186 km.) was, therefore, constructed to connect Medani and Khartoum. Construction started in 1967 and the road was opened to traffic in 1973. Construction of the Khartoum-Jebel Aulia (35 km.), Khartoum-Geili (44 km.), and Khartoum-Wadi Saiydna (20 km.) roads followed. These latter three roads, completed by the 1960's, constitute portions of long-distance intercity roads that were intended to connect Khartoum and Kosti, Khartoum and Port Sudan via Atbara, and Khartoum and Merewe, respectively. Other

roads, surveyed but not built, included Nyala-Zalengie and Malakal-Rebek. The only paved road constructed outside the northeast regions was Delling-Kadugli (186 km.) mainly to provide access to the commercial agricultural products of the Nuba Mountains area.

Whereas construction of paved roads during this period was limited to particular regions, especially Khartoum, earth tracks were continually being created by the traffic everywhere throughout the Sudan. Local short tracks continued to connect to each other and consolidate into defined long-distance vehicle routes linking supply and demand points as well as major population centers such as El Obied, Sinnar, Kosti, Atbara, Medani, Gedaref, Kassala, Khartoum, and Port Sudan.

Most of the construction of the intercity road network described was financed out of the development budget.* The 260 agricultural and industrial development projects suggested by the Ten-Year Plan left very little investment capital for road projects during this period. Of the L$2.2 million that was allocated to the transportation and communication sector in the plan, the share for building roads was only 3%. The limited road improvements were, however, largely consistent with the country's general project-oriented economic development framework.

It seems apparent that the government did not want to expand the road transportation system because it assumed that the private sector would have the lead in the development of road transportation services. The pattern of economic development and resulting increase in transport

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*It was financed largely by the United States Agency for International Development (AID).

demand observed in the Sudan during this period resulted in modern road development only in areas of population and economic concentration, i.e., in the already developed regions of Blue Nile and Khartoum. In the process of this market-oriented development, road transportation was left to free market forces. The outcome was an improved network that was quite limited and fragmented, a fact that proved to have the serious consequence of retarding the growth of the stock of commercial vehicles (82).

The Post-1973 Period

Until 1973 the Sudan completed only 400 km. of short distance intercity paved roads of which the most important is the Khartoum-Medani linkage. The rest are mostly short-distance roads linking major urban centers with their surrounding townships. The Five-Year Plan (1970-1975) placed very little emphasis on the expansion of the road network. An initial allocation of L$3.1 million was made for roads in the 1970-1975 Five-Year Plan. Special emphasis continued to be given to agricultural expansion. In 1973 the government revised some of the policies, priorities, and investments included in the Five-Year Plan. Accordingly the original plan was extended and the new 1970-1977 Plan was adopted.

The 1970-1977 Plan shifted the development emphasis from agriculture to industry. This shift is demonstrated by the increase in development expenditure for industry from 15% of total public development expenditure in the original Five-Year Plan to 34% in the 1970-1977 Plan, and the decrease of agriculture allocation from 33% to 25%. The

basic idea behind this change in priorities was to develop import-substitution industries to meet most domestic requirements, through local production and to increase the local value added of agricultural exports. As a result of this emphasis, the share of industry to GDP increased from 2% in 1970 to almost 9.4% in 1977. Food, textile, cement, sugar, kenaf, and fertilizers were among the most expanded industries. Major changes occurred in the field of agriculture as well. Mechanized rainfed agriculture increased in area from 1.0 million ha. to 1.2 million ha. Pump irrigation schemes were consolidated, expanded, and supplied with electric power. As a result of this expansion, the production of wheat, groundnuts, and rice (which was introduced in the Blue Nile region for the first time), increased substantially during the 1970-1977 period.

During this same period of the extended plan, the level of urbanization increased from 18% of total population in 1970 to 29.4% in 1976. Internal migration and movement of laborers to work in modern farming schemes increased. In 1974 the Gezira Scheme (in the Blue Nile region) alone employed more than 542,000 persons in harvesting the cotton crop, of whom 336,000 were from outside the region itself, mainly from the Western region (75). The annual migration to the mechanized farming scheme in Kordofan amounted to 70,000 people. Similarly, in Kassala region about 100,000 migrants from the Western and Northern regions travelled annually to agricultural schemes to obtain seasonal employment (75).

The economic developments discussed stimulated traffic substantially. Initial rail and road installations could not cope with the

increased traffic. Freight and passenger traffic increased annually at a rate of 8.8% and 7.5%, respectively, during the 1970-1977 period. Intercity road freight traffic was expanding faster than the passenger movements by buses and trucks. Available transport capacity became a severe bottleneck in the growth process. Port congestion increased due to slow clearance of cargo unloaded from the vessels for movement to the hinterland (96, 1977).

As soon as the need for rapid expansion of road transport facilities was felt, the L$2.2 million initially allocated for roads in the Five-Year Plan (1970-1975) was raised to L$27 million in the amended plan (1970-1977). This share constituted almost 50% of the transportation sector's share in total public allocations. The yearly budget allocations for the construction of roads during the plan period added up to L$107 million (97).

This shift of emphasis from other forms of transportation to road transportation was meant primarily to strengthen the network by removing bottlenecks in the movements of goods and people, and to provide a foundation for accelerated development in the future based on road transportation.

A program of building 1,415 km. of paved roads and 200 km. of gravel roads was undertaken in the extended plan (1970-1977). The major emphasis was on the construction of trunk roads which would provide connections between supply and demand points and connections between important population centers, thus providing an efficient system of roads for the movement of freight and passengers. The major road

projects carried out were Medani-Gedaref (227 km.), Gedaref-Kassala (220 km.), Kassala-Haiya (350 km.), and Haiya-Port Sudan (206 km.). These connected roads form an artery which connects the Blue Nile and Kassala regions with each other and with Port Sudan, thus filling in the connection between Khartoum and Port Sudan. Other road projects undertaken during this period were Medani-Sinnar-Kosti (217 km.), Nyala-Kas-Zalingie (215 km.), and the extension of the Kadugli-Delling road to Dibeibat town in Kordofan. By the end of the planning period in 1977, about 528 km. of these national roads were asphalted, 200 km. were gravelled, and about 360 km. of existing roads were maintained. The rest of the program was scheduled for completion during the Six-Year Plan period 1977-1983.

The Six-Year Plan (1977-1983) placed special emphasis on the expansion of the road system by allocating a sum of L$249.54 million for the road sector. This amount constitutes 50% of total public and private allocation to the transport and communications sector. Besides eliminating the severe bottlenecks, the main focus of the plan is directed to meet specific transport requirements which are likely to be generated by the other sectors of the economy. The expansion in road transportation capacity is being provided to cater to the transport requirements of industrial production expanding at a rate of 9.5% per annum and the projected growth in agriculture of 6.5% per annum (91). Investment priorities are, therefore, attached to the quick completion of the remaining sections of the Khartoum-Port Sudan road artery and to the new projects included in the plan for which the preliminary studies

indicated satisfactory returns. These latter projects are designed to link Port Sudan with major consuming and producing centers stretching up to Damazine and Kosti cities in the Blue Nile region. In addition, and for the first time, feeder road facilities to the major rail heads have been provided for in the plan. In all, a total length of 1,547 km. of paved trunk roads and 400 km. of feeder roads are scheduled to be added to the existing road network. By 1983 the intercity paved road network in the Sudan is expected to increase from the present 1,073 km. to 2,508 km. The long-run policy is to further expand the road system in the Sudan. There are more than 22 proposed road projects at present. Most of them are feeder roads. Some of these projects have been completely designed and are now under negotiation for foreign financing. Feasibility studies have been completed on others; and some have been proposed for feasibility studies. All in all, the road projects proposed for long-run planning comprise a total of 5,983 km. The expanded paved road network is depicted in Figure 8.

General Pattern and Characteristics of the Sudanese Road Network

Figure 9 shows the present gravel and earth road system of the Sudan described in the preceding analysis. Paved roads are shown in Figure 8. Generally, about 400 roads were estimated to exist with lengths varying from 10 to 1,825 km., connecting all towns of any importance in the country (70). The total length of these tracks is 45,000 km. If one assumes that the width of each road is only 2 meters, then the road system would comprise an area of 90,000 sq. km.; this area

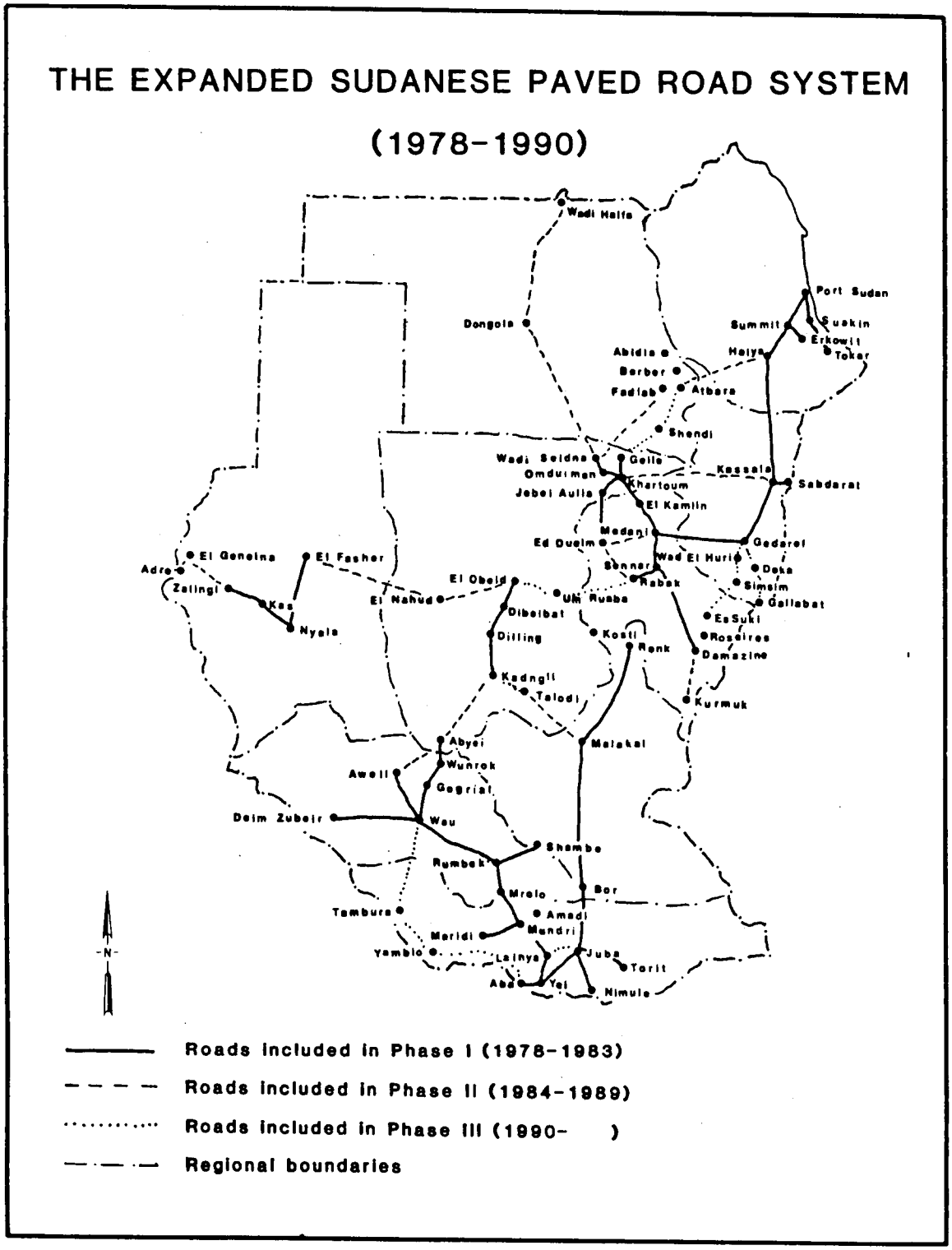


Figure 8. The expanded Sudanese paved road system (1978-1990).

Source: Based on information obtained from Sudan Ministry of National Planning, Road Toll Financing Feasibility Study, Khartoum, Sudan, 1978.

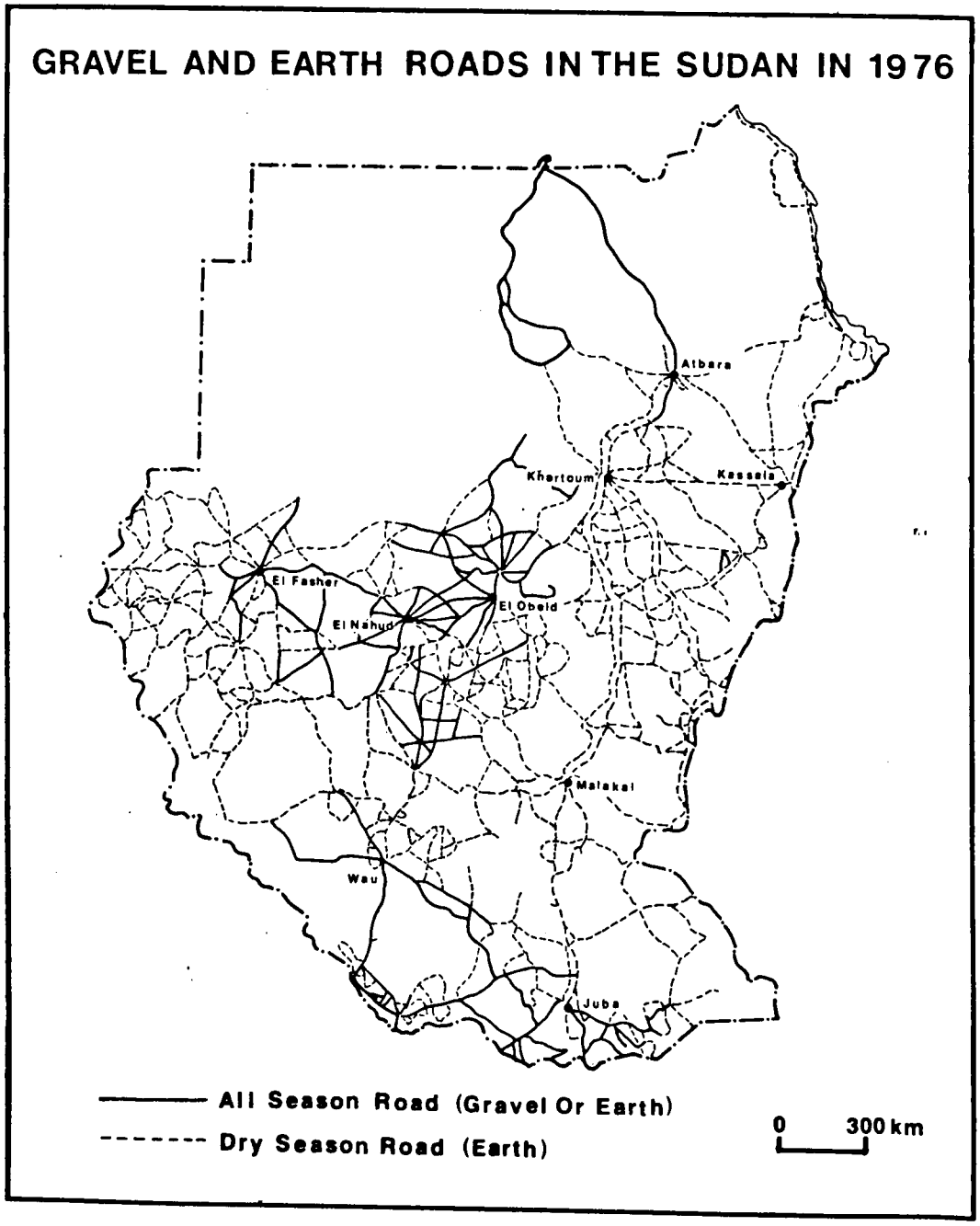


Figure 9. Gravel and earth roads in the Sudan in 1976.

Source: Sudan Survey Department, Khartoum, Sudan, 1976.

constitutes about 3-5% of the total area of the Sudan. The road system shown on the map (Figure 9), however, could be misleading because most of the earth roads are tracks whose condition depends on the soil and rainfall characteristics of the area. In some of the open regions these tracks may be several hundred feet wide and their location may vary considerably from year to year depending on the route taken by the first vehicle through, after the rains. It was, nevertheless, estimated that there are about 14,399 km. of defined earth roads in the country, 6,000 km. of gravel surfaced roads mostly in the Southern region, and more than 1,100 km. of paved roads mostly in the northeast region of the Sudan (103, vol. 2). The rest of the roads are undefined tracks. Based on these figures of road lengths, the length of paved and gravel surfaced roads per square kilometer of land area is about 0.003 km. This figure is low if compared to similar indices in many other developing countries (103, vol. 2).

An inspection of the map (Figure 9) shows three isolated areas of all season roads: the Equatoria region, western parts of Kordofan region, and the northern part of the Northern region. Roads located on the Equatoria region owe their existence to the availability of laterite which is an excellent road building material. Although this is a high rainfall, the nature of the laterite soil helps keep roads passable virtually all the time. A comparison of the location of the all season roads of the Kordofan region with the soils map (Figure 10) will show that all these roads are in the sand (Qoz) area. Indeed, this is the reason that they are all season in nature. Composed of deep porous

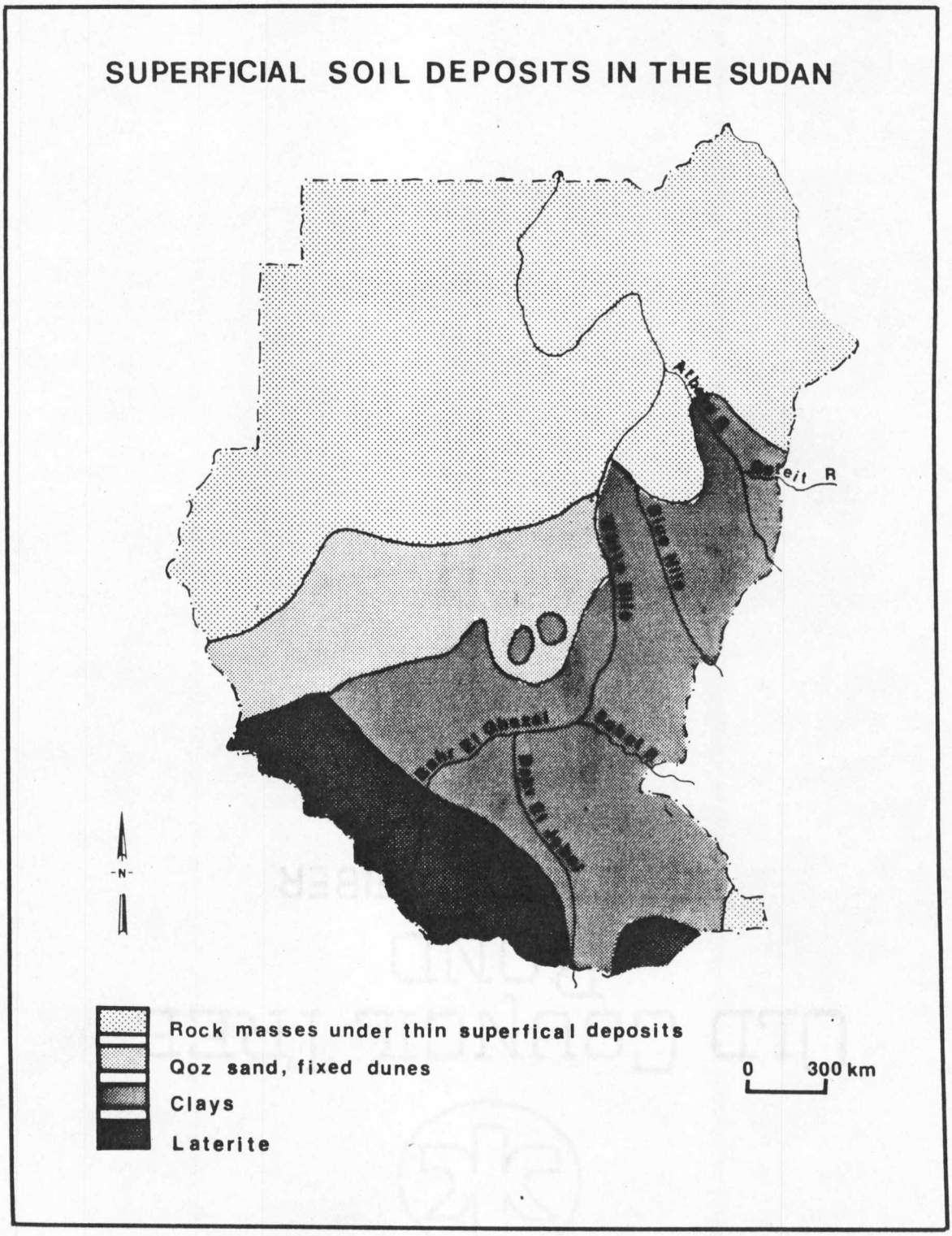


Figure 10. Superficial soil deposits in the Sudan.

Source: Sudan Survey Department, Khartoum, Sudan, 1955.

sand, and relatively homogeneous in texture, the rain drains through the sand as soon as it falls so the tracks are functional during the rainy season and are not destroyed. Thus, the roads in this area are classified as all-season roads. The few all-season roads in the Northern region are again only tracks and are used in all seasons only because there is virtually no rain in this area.

The dry weather roads are located on the central regions, southern parts of Darfur and Kordofan regions, the Blue Nile, Upper Nile, Kassala, and the northern part of Bahr El Ghazal regions. These are the clay and clay-silt soil areas. The clay soils become more or less flooded in rainy season, get wetted by water sweeping into the cracks that develop in the dry season. When dry an initial permeability of 40 $mm\text{-}h^{-1}$ was noted, typical of the reaction of wet clay soils to the first rains, when they are cracked and dry (104). This permeability drops to 0.2 $mm\text{-}h^{-1}$ when the soil gets swollen and the cracks become closed. Cracking patterns have a depth of more than 2 meters with width ranges from 2 to 10 cm. (104). Because of these characteristics, tracks are not negotiable by wheeled vehicles when wet. They remain unusable until the clay is dry. Some roads may be open as little as two months per year as in the Upper Nile region or as much as ten months per year as around the Khartoum region.

Vehicle speed and travel time varies depending upon season of the year and type of soil traversed. Table 14 shows general characteristics of some road systems in the Sudan and performance under normal (dry) and low capacity (wet) seasons. It should be noted that vehicle speed

Table 14

General Characteristics of Road Systems in the Sudan

Road Name	(km)	Type	Usable	Travel Time in Normal Season (hours)	Travel Time in Low Capacity Season (hours)
Khartoum-Medani	187	Asphalt	All	3	3
Khartoum-Atbara	312	Earth	All	12.5	12.5
Khartoum-Kosti	312	Earth	Dry	12.5	12.5
Khartoum-El Obeid	413	Earth	All	20.5	20.5
Khartoum-Kassala	400	Earth	Dry	14	Closed
Khartoum-Dongola	547	Earth	All	26	26
Port Sudan-Haiya	225	Asphalt	All	4.4	4.4
Port Sudan-Tokar	160	Gravel	All	5	5
Kassala-Haiya	350	Asphalt	All	6.4	6.4
Haiya-Atbara	291	Earth	Dry	12	24
Gedaref-Kasala	223	Asphalt	All	4.4	4.4
Gedaref-Gallabat	150	Earth	Dry	5.5	Closed
Gedaref-Medani	235	Asphalt	All	4	4
Sennar-Medani	126	Asphalt	All	2.5	2.5
Sennar-Kosti	103	Earth	Dry	3.5	Closed
Kosti-Malakal	508	Earth	Dry	21	Closed
Kosti-El Obeid	320	Earth	Dry	14	28
El Obeid-Kadugli	298	Gravel	All	9	9
El Nahud-El Fashar	452	Earth	All	22	22
El Obeid-El Nahud	215	Earth	All	10.5	10.5
El Nahud-Wau	675	Earth	Dry	23	66
El Nahud-Nyala	523	Earth	Dry	25	50
Nyala-Wau	690	Earth	Dry	33.5	66
Nyala-Zalingi	205	Earth	Dry	10.2	20
Nyala-El Fasher	225	Earth	All	11	11
El Fasher-El Geneina	356	Earth	Dry	18.35	35
Sennar-Roseires	248	Earth	Dry	10.25	Closed
Dibeibat-Dilling-Kadogli	186	Asphalt	All	3	3
Wau-Juba	850	Gravel	All	25.8	25.8

Source: A. S. Norconsult, Feasibility and Preliminary Engineering Study (Kosti-Umm Ruwaba Road) (Final Report), text volume, Khartoum, Sudan, 1978.

during normal season is generally lower on sand and desert soils (16 km./hr.) than on clay (48 km./hr.). But during the wet season speed over sand soil increases to 40 miles per hour, on the average. Also travel time over clay soils during the rainy season is as much as twice (or more) that during the dry season. Generally, sandy soils are permeable and discharge water rapidly, providing soft stable track surface; clay soils are of low permeability, subjected to flooding, and when dry they crack, providing rough driving conditions.

In Chapter III the Sudanese regional economy and its development potential have been examined and structurally different regions have been identified. Then the relationship between this regional economy and amount of traffic has been established. In Chapter IV the utilization of the intercity road network system has been shown by examining the interregional economic structures and identifying various regions as sources of origins and/or destinations, the magnitude and pattern of flows between supply and demand points, and the characteristics of the traffic which include features like hauling distance, load factor, truck annual-kilometers, etc. Because the utilization of the road network depends upon transportation characteristics of the various network linkages, these characteristics, which include link type, seasonality, travel time, speed, etc., have been discussed in the present chapter. The effects of these characteristics on the level of service offered by the system have also been shown. Given an increasing demand for transportation, a set of spatially separated supply and demand points, and the current low level of service on the Sudanese road network system,

efficiency has become a critical factor in overall development of the road system in the Sudan. This transportation efficiency and its improvement will be examined in the second part of this study.

CHAPTER VI

THE MODEL: ITS THEORETICAL AND STRUCTURAL SETTING

Theoretical Setting of the Model

In the initial planning process, maintaining efficiency in the level of service is the sole objective of Sudanese officials in their road transportation development program. Efficiency may be enhanced through upgrading road surfaces from earth to gravel, gravel to pavement, or earth to pavement, subject to the available budget for such improvements. Each road link in the network has been identified by existing road surface type. Each type of a road has a level of service as measured by average speed, travel time, operating costs, and other measures. These measures can be expressed individually or collectively as weights associated with each road surface type. These weights might be interpreted as impedance values; the higher the weights the higher the travel time and/or operating cost. Weights will, therefore, reflect the specified measure of the level of service for the different classes of road.

Improvements of the road links would normally result in reduction of the total sum of weighted ton-kilometers used by the road system. The weighting scheme will allow measurement comparability as ton-kilometers on different road types can be added together in commensurate units. The development strategy involved here is, therefore, one in which a decrease in a given amount of total weighted ton-kilometers

utilized by the road network system is compared against the expenditure of additional funds earmarked for transportation improvements. This implicit tradeoff may be formalized as an objective function of the following type: minimize the total sum of weighted ton-kilometers on earth, gravel, and pavement roads, subject to a given budget which limits total expenses incurred. This budget is, therefore, an exogenously determined amount of money available for total improvements in the links.

In formulating the model, it is assumed that the country may be subdivided into different regions where a large number of economic activities are being carried out. A demand for road transport facilities exists between the various regions of the country and, at a maximum, the magnitude of this demand depends on the land resources and population densities of the regions. All economic activities and resulting traffic movements are assumed to take place between regional capitals (cities) each of which is chosen as a punctiform representation of regional demand in a network formulation, i.e., all regional demand is assumed to be located at a point (the regional capital).* Each region is an origin and destination for traffic and flows originating in or destined to a given region are, therefore, assumed to emanate from that particular city. The volume of interregional traffic is projected for the year 1985 and represents freight tonnage demand that will be

*In his study, "A Mathematical Programming Approach to a Network Development Problem" (3), Barber noted that this assumption is not overly restrictive. It has been made by both Kresge and Roberts, and Harris in two quite different contexts (3).

moved between each origin-destination pair according to the planning study of Adar. Passenger flows are not considered in the model because of lack of complete data. Flows represent various sets of commodity classes aggregated into one. Demands (flows) are not a function of level of service on the network, but they are known and fixed. This underlying assumption of fixed demand reduces the investment problem to measuring the total cost of travel incurred in using the network or a minimization of total weighted ton-kilometers in the road network. In any case, however, investment planning will be relied upon to meet this 1985 forecast.

If traffic movement takes place among specified cities and is confined to routes among these cities, then the spatial aspects of the transportation process may be represented by means of a network graph composed of a set of nodes and links. The nodes correspond to cities and the links correspond to roads. A road network defined by these nodes and links is assumed. Existing interregional linkages are defined by links that best represent the connections among various nodes. The formulation deals only with movement between regions; intraregional linkages are, therefore, ignored. Improving the efficiency of intraregional transportation would make an interesting and important comparison study.

Demand between each set of node pairs can be met by means of a combination of a set of connected links called routes (paths). These routes must be well specified. It is assumed that each origin-destination demand is served by the shortest weighted path. The

shortest weighted path is the path connecting the origin and destination that has a combined minimal length. The combined weighted length of a path is equal to

$$w_e(l_e) + w_g(l_g) + w_p(l_p)$$

where, w_e, w_g, w_p denote weights determined on the basis of relative average travel time for earth, gravel, and paved roads, respectively; and l_e, l_g, l_p represent total length of earth roads in kilometer per path, total length of gravel roads in kilometer per path, and total length of paved roads in kilometer per path, respectively.

Demand between each pair of nodes is assumed to be met by a single shortest weighted path (defined in terms of minimum relative travel time) connecting those nodes. Capacity is, therefore, not considered in the model. All links are assumed to operate well below their capacity, a reasonable assumption in a country like the Sudan. This assumption rules out congestion effects on roads between regions. Improvement in the level of service is assumed to increase in any link of the network in a continuous fashion. Since investment is measured in terms of the total number of kilometers of a particular road that is upgraded, the amount of investment would be dependent upon the type of road surface and associated flow, and total length of the link.

The preceding discussion indicates the form that the objective function will take. Also indicated is the nature of budget and demand constraints. Aside from the non-negativity conditions on all the variables, two additional sets of constraints are necessary to make the

solution to the problem internally consistent. These two constraints indicate bounds on the initial amounts of earth and gravel road types available (i.e., length of earth and gravel roads). These two sets of constraints would make it impossible to upgrade beyond what is initially available.

Structural Setting of the Model

Given a network which consists of nodes connected by a set of links uv, demands measured in tons of commodities, and a budget for road improvements, a mathematical formulation of the investment problem posed is given by a nonlinear quadratic objective function and a set of linear constraints as follows:

Let, D_{ij} = total demand at node j from node i

X_{ij}^{r} = amount shipped from i to j over route r in tons

R^{r} = set of links (u,v) in the rth route connecting (i,j)

W_e = weight attached to ease of travel (i.e., travel cost) on earth road segments

W_g = weight attached to ease of travel (i.e., travel cost) on gravel road segments

W_p = weight attached to ease of travel (i.e., travel cost) on paved road segments

EE_{uv} = number of kilometers of road link (u,v) that remain earth after investment

EG_{uv} = number of kilometers of road link (u,v) that are upgraded from earth to gravel

EP_{uv} = number of kilometers of road link (u,v) that are upgraded from earth to pavement

GP_{uv} = number of kilometers of road link (u,v) that are upgraded from gravel to pavement

R = the set of all links on network

$n(i,j)$ = number of routes between i,j

e' = number of kilometers of link (u,v) that are earth before investment

g' = number of kilometers of link (u,v) that are gravel before investment

p' = number of kilometers of link (u,v) that are pavement before investment

C_{eg} = per-kilometer cost of upgrading earth to gravel

C_{ep} = per-kilometer cost of upgrading earth to pavement

C_{gp} = per-kilometer cost of upgrading gravel to pavement

B = total budget allocated to road work.

Objective function:

$$\text{Min } Z = W_e \cdot \Sigma_i \Sigma_j \left(\sum_{r=1}^{n(i,j)} X_{ij}^r \cdot \sum_{(uv) \epsilon R_{ij}^r} (e'_{uv} - EP_{uv} - EG_{uv}) \right.$$

$$+ W_g \cdot \Sigma_i \Sigma_j \left(\sum_{r=1}^{n(i,j)} X_{ij}^r \cdot \sum_{(uv) \epsilon R_{ij}^r} (g'_{uv} - GP_{uv} + EG_{uv}) \right.$$

$$+ W_p \cdot \Sigma_i \Sigma_j \left(\sum_{r=1}^{n(i,j)} X_{ij}^r \cdot \sum_{(uv) \epsilon R_{ij}^r} (p'_{uv} + EP_{uv} + GP_{uv}) \right.$$

Subject to:

$$(1)\quad \Sigma_r X_{ij}^r = D_{ij} \quad \text{For each i and j where, } i \neq j.$$

$$(2)\quad EP_{uv} + EG_{uv} \leqq e'_{uv}$$

$$(3)\quad GP_{uv} \leqq g'_{uv}$$

$$(4)\quad C_{eg} \cdot \Sigma_{(uv)\epsilon R} (EG)_{uv} + C_{ep} \cdot \Sigma_{(uv)\epsilon R} (EP_{uv}) + C_{gp} \Sigma_{(uv)\epsilon R} (GP_{uv}) \leqq B$$

$$(5)\quad EG_{uv} \geqq 0,\ EP_{uv} \geqq 0,\ GP_{uv} \geqq 0,\ X_{ij}^r \geqq 0.$$

The objective function indicates minimization of total ton-kilometers moved on each of earth, gravel, and pavement surfaces between all nodes i and j in the system. Note that the function minimized is quadratic where total minimum ton-kilometers is a function of a link flow variable and distance or road length. Constraint (1) requires that for each pair of nodes i j, the sum of shipments into j should equal the total demand required at that node j. Inequality (2) indicates that the total number of kilometers on a link uv that are upgraded from earth to pavement plus the number of kilometers left earth after investment should be less than or equal to the total number of earth kilometers of that link before investment. Inequality (3) means that the number of kilometers that are gravel of link uv which is upgraded to pavement should be less than or equal to the initial number of kilometers of gravel of link uv. Inequality (4) means that the total sum of all upgrading costs should be less than or equal to the available budget allocated for road work. Inequalities (5) require that there should be

no negative flow on any link and no negative investment. In the next chapter this investment model is calibrated and applied to an inter-regional transportation network defined for the Sudan.

CHAPTER VII

MODEL CALIBRATION, SOLUTION PROCEDURE, AND APPLICATION

Calibration of the Model

The model described in the preceding chapter is applied to the interregional road network in the Sudan. The aim is to define optimal accomplishment of all necessary road transportation improvements subject to the available budget and a set of future traffic demands. Investment decisions are based on the number of kilometers a particular road link, or portion of it, that is to be upgraded from earth to gravel, gravel to pavement, or earth to pavement. Investments are to be made so that overall interregional road transportation system is as efficient as possible as measured by minimizing total weighted ton-kilometers.

The location of the ten regions within which Sudanese road transportation network improvement is considered is shown in Figure 1, p. 32. The first part of this study provided a general background to the necessary data used to calibrate and execute the present model. Basic to the investment program are data on the physical quantities of commodity flows between regions. The main source from which these data are obtained is the Adar study of 1974 (103). In that report, production and consumption figures by region and by commodity were estimated for 1973 and projections for 1985 were provided. Based on those production and consumption estimates, which take into consideration the evolving space economy of the Sudan detailed in Chapters III and IV,

surpluses and deficits by region were calculated for each commodity. Then using a linear programming model, the surpluses for any given commodity were routed from the surplus nodes to the nearest node having a deficit of the commodity. This allocation procedure continued to other deficit nodes until all deficits were met or the surplus was exhausted. National surpluses, if they existed, were routed to the port for export. Likewise, national deficit was considered to be met by import through the port. In this way a series of commodity flows between regions was obtained. Flows were then aggregated over all the commodities examined into five general commodity classes. These flows, tabulated in matrix form in second volume of the Adar study, are utilized in this study (103).

As might be expected in a developing country, some deficiencies are found in the Sudanese data base. Adar's 1985 estimates were formulated on the basis of inadequate commodity flow data. One might, therefore, expect some margin of error in those data projections. Despite this limitation, however, Adar's traffic data represent almost every possible commodity produced in the Sudan, and the projections were accepted by Sudanese officials as the best data and projections available. Adar's data are the most recent, most complete and most reliable data available to calibrate the model. If time and resources would have permitted, it would have been desirable to generate production and consumption estimates for a base year on the basis of some recently available information in the Sudan, make long-range projections beyond 1985, calculate surpluses and deficits, and then use the linear programming

technique as part of this study to determine interregional commodity flows. These flows could be used to calibrate the model and to conduct sensitivity analysis to see the effect of change in demand. Such a task of generating more recent long-range projections was beyond the scope of the present research.

The traffic flows projected in the Adar study for five classes of commodities were aggregated into one class to obtain the total tons in an origin-destination framework. Because other modes of transportation are available which could be used to move the commodity traffic, it is assumed that 50% of the flows move via road transportation. This percentage was judged on the basis of relative share of road transportation in the movement of total freight traffic in the Sudan over the last several years vis-a-vis the share of other means of transport (see analysis in Chapter IV). The effect of this assumption about road traffic on results of the study could best be known by testing the sensitivity of the result to this specific assumption. Such a test, however, has not been attempted in this study because of data limitations on commodity demands.

The aggregation of commodities into one category was dictated mainly by the requirements of the objective function form in the model which is designed to minimize total weighted ton-kilometers on earth, gravel, and paved roads. This aggregation is likely to have a minimal or no effect on the results and conclusions reached in the study. As will be seen in the next section, the heuristic method utilized to solve the model involves solving shortest path and optimization problems. The

routing of commodity flows between and through each nodal pair in the model (to determine shortest weighted routes) is not based on minimum transportation cost which may vary according to the type of commodities moved, requiring, therefore, that these commodities be considered in their disaggregated form lest the investment decisions (which are based on minimizing cost) be affected. Rather, this routing in the model is based on minimum relative travel time which can be used uniformly with the one class of aggregated commodities analyzed in the study.* In addition, determining investments in any study of road transport improvement would be dependent upon total traffic which is normally an aggregate of passengers and commodities of different sectors of a country or region's economy studied. Therefore, as far as final investments to be determined in this study are concerned, it appears that there is no loss in generality in considering one class of aggregated commodities in the model.

The investment model is calibrated for the Sudan using the 1979 physical interregional road transportation system characteristics. This interregional network was specified as it existed in 1979. It consists of ten nodes and fifteen links. The nodes and the links are mapped in Figure 11. The road links are shown in solid lines and the nodes are shown as small circles. Since road link type and length is the most important decision variable, each link (uv) is specified in terms of its surface type component, i.e., earth ($e^{'}$) and/or gravel ($g^{'}$) and/or

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*It would be easy in this study to extend the shortest path program, but not the optimization program when there is more than one category of commodities.

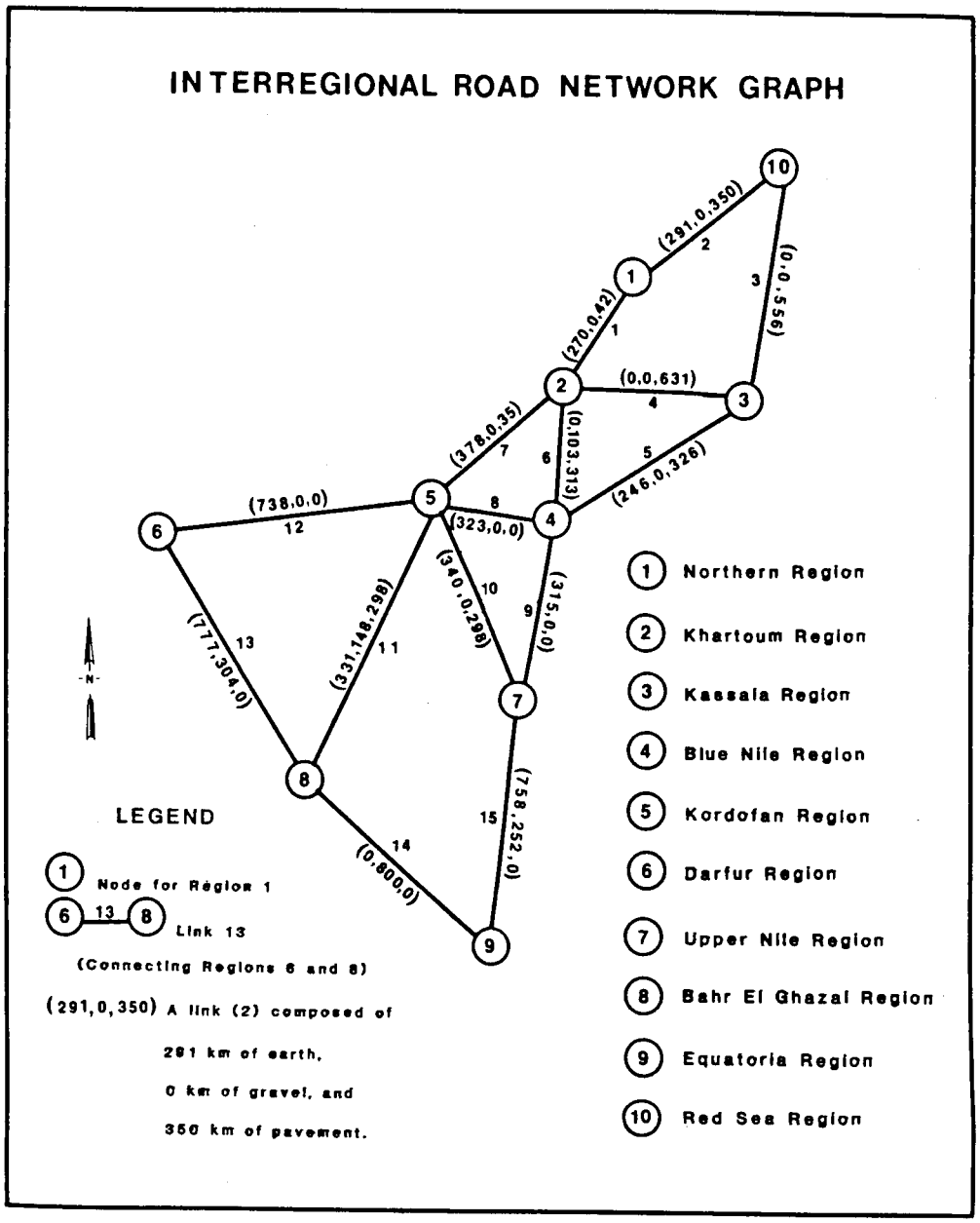


Figure 11. Interregional road network graph.

pavement (p'). The links are also numbered from 1 to 15. Total length of the link and the portions that are earth, gravel, or pavement, respectively, are shown along each link. These links lengths represent actual road distances and data about them were obtained from various available sources. The links shown in the figure represent specific spatial connection of a road system shown in Table 15. As shown in Figure 11, the road system considered seems to be simple but the dimension of the network structure becomes rather complex when viewed in a context of the several investment alternatives (i.e., earth to gravel, gravel to pavement, and earth to pavement).

The weights (w_e, w_g, w_p) associated with each type of road class are taken to be 3, 2, and 1 for earth, gravel, and paved roads, respectively. These weights were determined generally on the basis of actual average travel times over various link types for which data were available, and to reflect other operating characteristics over various link types of the Sudanese road network system under different physical and climatic conditions (see analysis and tables in Chapter V). It has been noted previously that travel time over earth road in the Sudan is in most cases three times that on paved roads, whereas travel time over gravel road is twice as that on paved roads (see Table 14, p. 116).

Whereas these weights were determined on the basis of relative travel time, they may also reflect other link performance measures such as speed and risk of delay due to weather conditions. This is so because travel time over the Sudanese road network is to a large extent a function of seasonal delay factors caused by variations in rainfall and soil permeability. The weights could, therefore, be construed as

Table 15

Spatial Connection of the Interregional Road System
Considered in the Study

Link #1	Connecting nodes	1,2	: Khartoum-Gaili-Atbara
Link #2	Connecting nodes	1,10	: Atbara-Haiya-Port Sudan
Link #3	Connecting nodes	10,3	: Kassala-Port Sudan
Link #4	Connecting nodes	2,3	: Khartoum-Gedaref-Kassala
Link #5	Connecting nodes	3,4	: Kassala-Sennar-Kosti
Link #6	Connecting nodes	2,4	: Khartoum-Kosti
Link #7	Connecting nodes	2,5	: El Obied-Khartoum
Link #8	Connecting nodes	4,5	: Kosti-El Obied
Link #9	Connecting nodes	4,7	: Kosti-Jebelein-Renk-Malakal
Link #10	Connecting nodes	5,7	: El Obied-Kadugli-Malakal
Link #11	Connecting nodes	5,8	: Wau-Aweil-Kadugli-El Obied
Link #12	Connecting nodes	5,6	: El Obied-Nyala
Link #13	Connecting nodes	6,8	: Nyala-Meshra-Wau
Link #14	Connecting nodes	8,9	: Wau-Tonj-Rumbeek-Amadi-Juba
Link #15	Connecting nodes	7,9	: Juba-Bor-Malakal

measures of various levels of service rather than travel time only. Crude as they are, the weights are, more or less, sufficiently accurate to differentiate between road classes in terms of their level of performance.

Before determining per-kilometer costs required to raise road links to successively higher levels of service, the design standards of proposed changes to the network need to be specified. These standards were set to be a two-lane road of bituminous surface treatment for paved roads and a two-lane all-weather road for gravel roads. Earth roads are assumed to be graded before being improved to another surface material. Detailed descriptions of these design standards are available in chapter ten of the Norconsult study (118), chapter six of the Norconsult inception report (119), and chapter five of the Berger study (116). It should be noted that the design standards chosen are generally consistent with the prevailing trend of road building in the Sudan.

Three investment costs are required to calibrate the model: per-kilometer cost of upgrading an earth link to gravel, a gravel link to pavement, and an earth link to pavement. Data on the later cost (earth to pavement) were obtained from the Road Toll Financing Feasibility Study of 1978 (98). The report provides a list of road projects which are likely to be completed by 1983 and their estimated costs. These per-kilometer costs vary from L$84,000 to over L$179,000, depending on the regional location of a road project. Road construction costs in the Sudan reflect existing regional variation in the availability of construction materials and water as well as the nature of

soils (118) and (121). To arrive at an estimated per-kilometer cost of upgrading earth road to pavement and use it to calibrate the model, the estimated average per-kilometer costs of all road projects in the list available in the report (about 10 road projects) were summed and the average was computed. The figure obtained (L$98,000) does not differ much from figures obtained in previous studies such as the Norconsult study of 1978 where average per-kilometer cost of building paved roads with a bituminous surface treatment was estimated at L$95,000. Taking into consideration cost differences resulting from inflation effects between 1978 and 1979, the L$98,000 figure obtained here seems quite appropriate to be utilized to calibrate the model.

To obtain estimates of per-kilometer cost to upgrade a link from earth to gravel, per-kilometer costs estimated for seven road projects listed in the Berger study of 1974 (116) were summed and the average was calculated. The figure obtained is L$33,310. Because this figure reflects the 1974 prices, it was adjusted for inflation so that it would be appropriate for 1979. An escalation factor for the average per-kilometer cost was used based on percent increase in construction costs between 1974 and 1979. The derived figure is L$48,000 which is used in this study.

It was not possible to obtain actual costs of upgrading roads from gravel to pavement. This cost was assumed to be generally less than the cost of upgrading earth road to pavement and greater than the cost of upgrading earth to gravel. This cost was chosen to be L$59,000, a figure between the L$95,000/km. for earth-to-pavement improvements and L$48,000/km. for earth-to-gravel improvements.

Two things should be noted when considering upgrading costs utilized to calibrate the model. First, the per kilometer cost of upgrading earth to pavement roads was based on estimated project costs that were originally calculated on the basis of only direct construction costs (i.e., labor, equipment, and material costs), whereas the per-kilometer costs of upgrading earth to gravel roads were based on project cost estimates which reflect all cost components, including labor, equipment, material, custom duties, and land acquisition (i.e., total project costs). Whereas this problem of inconsistency related to the data base might create some discrepancy between the two costs considered (i.e., per-kilometer costs of upgrading earth road to pavement and earth to gravel), the margin of difference is deemed to be small [Norconsult (119) and Berger (116)]. This is true because construction costs for paved or gravel roads in the Sudan are overwhelmingly based on labor, equipment, and construction material costs; other cost components such as land acquisition and taxes constitute only a minor portion of total construction costs. Land acquisition and compensation cost per kilometer, for example, was estimated in the Berger and the Norconsult studies to be less than 1% of total road project cost.

Second, the investment costs considered for each link class represent estimated averages that may reflect approximate rather than exact measures of costs which in fact vary according to specific locations within the country; these costs should, therefore, be viewed with some caution. The fact that these costs are analyzed in the model in a context of mutually exclusive investment, would, however, minimize

the effect of these costs used, as they are approximate averages, on the results obtained in the study. In general, despite the limitations discussed, the data are among the best available for any less developed country and do not seriously limit the execution of the present model or affect the conclusions reached.

Finally, the model is solved for various budgetary levels set aside for road construction. The amounts of money chosen here range from L$100 million to L$250 million; these amounts coincide with the proposed investment fund allocated to road construction (totalled L$250 million) in the current Six-Year Plan 1977-1983.

Solution Procedure

The investment problem is a linearly-constrained nonlinear network flow programming problem. To my knowledge, no efficient exact algorithm has yet been devised to solve this class of problem. One has, therefore, to resort to heuristic techniques as the best available solution methods. The heuristic approach proposed and used to solve the present problem is a cyclic heuristic which will allow the quadratic programming problem to be reduced to a linear programming problem. the procedures involved in the cyclic heuristic can be conceptually described as follows.

The first step in the heuristic procedure will be to route total flows, using a shortest path algorithm, such that each i,j pair of nodes is assigned by the shortest weighted route based on relative average travel time. The shortest path (or paths) between i and j is thus

found. Once the shortest weighted route between each node pair is used, the second step is to determine number of total tons, T, being moved on each link uv; this is calculated as:

$$T_{uv} = \Sigma D_{ij}\, a_{uv}, \text{ for each ij pair of nodes}$$

where,

$$a_{uv} = \begin{cases} 1 & \text{if link uv is in the shortest route between i and j} \\ 0 & \text{otherwise.} \end{cases}$$

Since T_{uv} is defined, the problem is reduced to the following form:

$$\begin{aligned} \text{Minimize } Z = {} & W_e \cdot \Sigma_{(uv)\varepsilon R}\, T_{uv}\, (e'_{uv} - EP_{uv} - EG_{uv}) \\ & + W_g \cdot \Sigma_{(uv)\varepsilon R}\, T_{uv}\, (g'_{uv} - GP_{uv} + EG_{uv}) \\ & + W_p \cdot \Sigma_{(uv)\varepsilon R}\, T_{uv}\, (p'_{uv} + EP_{uv} + GP_{uv}) \end{aligned}$$

subject to constraints 2, 3, 4, and 5. This is a linear programming problem which could easily be solved using an available algorithm. Having obtained the weighted minimum-time routes fixed in this way for each pair of nodes, the first part of the solution process is completed. The other part is to solve the modified linear programming problem where routes are fixed and the optimal investment program can be determined.

The solution process briefly described above involves solving a series of shortest path problems. For each solution the optimization process involves examining each link in the network to determine how much load (tonnage) is obtained on a particular link; this is the total (accumulated) tonnage on that link. When total load is determined for

each link, these loads are evaluated by the model and in this application the ones with the highest feasible flow load are selected for upgrading. Then another set of shortest path problems are solved with the previously upgraded links included in the solution. The total loads and the links with the highest loads for investment are chosen as before. The process continues by solving many shortest path and optimization problems cyclically until a stable network emerges. The principal steps involved in the cyclic heuristic are schematically represented in Figure 12. Two computer programs are used to apply the heuristic: the shortest path program (called TALLYHO) and the Fixed Route Linear Programming (FRLP).

One note about the cyclic heuristic is that the traffic demand between node pairs is never changed by the physical routing of traffic in the solution process; all traffic follows the shortest route between its origin and destination node pair. What changes is the loading pattern of the traffic on the links on the shortest weighted routes. It should also be noted that while the routing process takes place, it by no means implies a process of flows allocation on a national basis which takes place like in a classical transportation problem where allocation is made so as to minimize some measure of system-wide improvement. Rather, flows here are allocated such that they are optimal from the viewpoint of a single origin-destination node pair; hence, the result is equivalent to the problem of investing to reduce the shortest weighted paths. It should be noted that the system-wide efficiency solution in this case is equivalent to the node pair solution as long as there are no congestion costs (57).

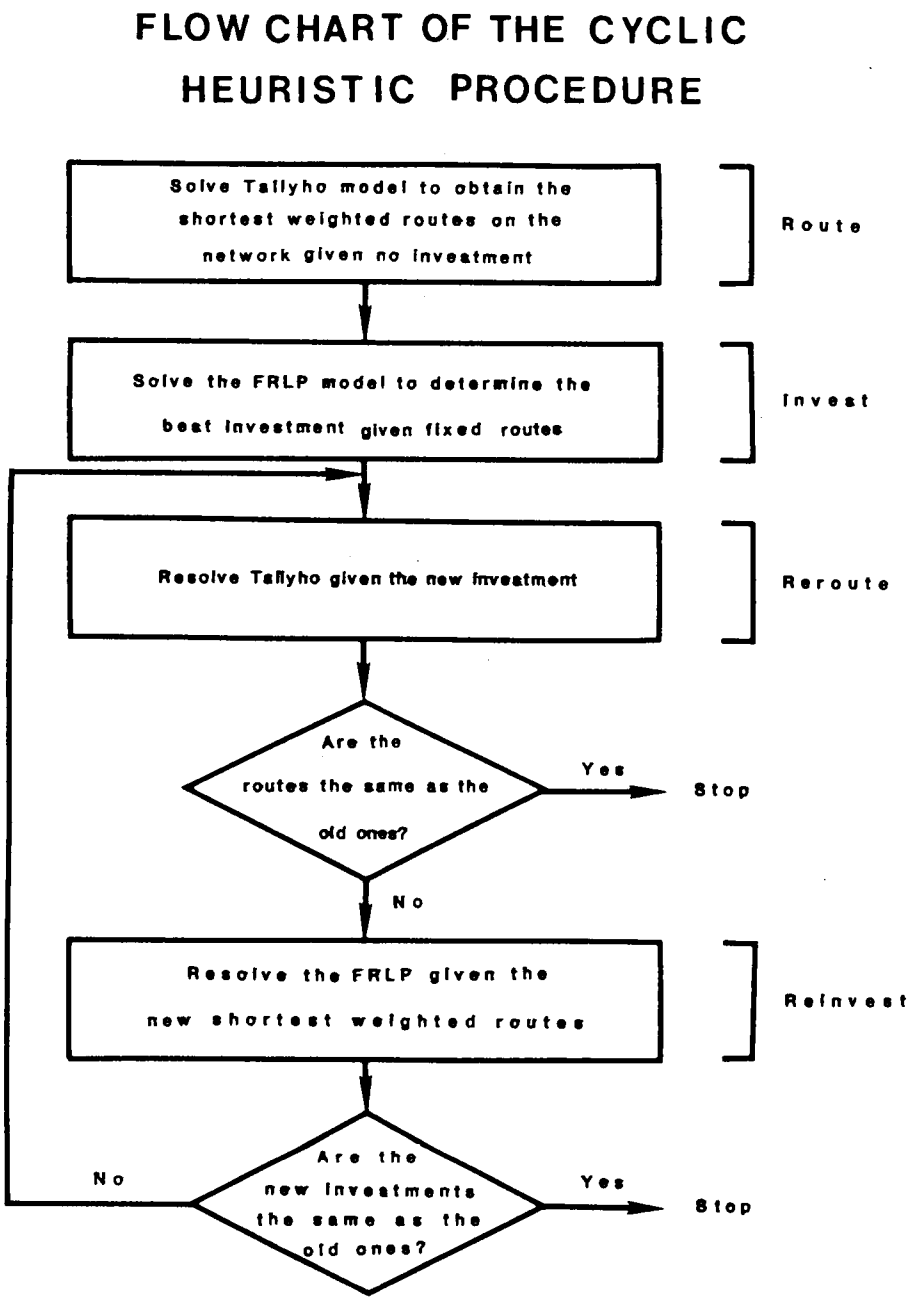


Figure 12. Flowchart of the cyclic heuristic procedure.

Also the cyclic heuristic procedure tests all possibilities for improving the links by starting a new cycle and new network information, taking into account flow interdependencies among the various links. That is, the upgrading of a new link will divert traffic from other links and may change the flow of shipments between origin-destination pairs. Thus the value of upgrading a particular link will be dependent on what other links have already been improved and added to the system. It is, however, quite possible that link improvement possibilities that were previously rejected (in step 2) may have an opportunity of being selected in a later cycle (in step 4) if the changes in loads make them relatively more attractive in terms of additional loads gained by those links. Likewise a link previously selected for improvement may be deleted in a later cycle because of loss in its tonnage load.

Each new cycle of the heuristic procedure starts with solving the shortest weighted path problem and ends with solving the optimization linear programming problem. This means that the number of cycles in which a particular final solution is generated is always equal to the number of optimization and/or shortest weighted path problems being solved in order to obtain that final solution. Finally, the heuristic does not guarantee a mathematically optimal solution. It will probably, however, produce an exact or a near optimal solution. At each step the heuristic does yield a feasible solution.

It should be noted that the design process of this heuristic is a fairly standard approach.* The cyclic heuristic solution process is similar to the manner in which real world decisions are made. The shippers determine the routes in the first place and use them, before any investment is made, showing how various people initially ship on the road system. This is the first part of the cycle of the heuristic. It is, therefore, known exactly how shippers are behaving; the routes and how much tonnage is crossing each link are also known, and, therefore, it becomes apparent where to invest so as to minimize total weighted ton-kilometers, completing, therefore, one cycle of the heuristic. The new investments would allow shippers to change their shipping behavior, therefore, resulting in changes in the pattern of shipping on various links of the system (the beginning of a new cycle). A new pattern of routes, therefore, emerges which reflects the response of the shipper to investments.** Further investments are needed and the process continues until shippers are satisfied or investment capital is exhausted and investments are stopped.

Application of the Cyclic Heuristic Procedure and Results

The cyclic heuristic procedure outlined in preceding sections and presented schematically in Figure 12 was applied to solve the investment

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*A number of similar heuristic procedures which are in practical use have been outlined and discussed by Steenbrink (57).

**It is implicitly assumed here that shipper responses are optimal, simultaneous and immediately consequent upon the alteration of the system.

problem for the Sudanese interregional road network. The FRLP program allows the modified (linearized) linear programming formulation to be structured into standard linear programming format and solved by the MPSX package of IBM. TALLYHO was written for this study. Both programs were written in Fortran IV for the IBM 360/3031 computer.

TALLYHO employs a shortest path algorithm developed by Dijkstra (57). The essence of the shortest path procedure is that it fans out from the origin node successively identifying the shortest weighted route to each of the nodes of the network in the ascending order of their shortest weighted relative travel times from the origin, thereby solving the problem when the destination node is reached.

The investment problem was solved for different levels of budget constraints, L$100, 125, 150, 175, 200, 225, and 250 million. Applying the model under these different levels of budget constraints permitted a sensitivity analysis to determine the relationship between amount of investment and changes in levels of network efficiency as measured by reduction in weighted ton-kilometers. The most appropriate budget level which maintained a high level of efficiency in the network should be chosen.

Results of a complete solution process completed in two cycles for the case of L$100 million budget level are reported in Appendix A. This case serves as an example to illustrate the application of the solution procedure and its steps as described below. For the rest of the solutions generated, however, only the results obtained in the final iteration are reported in Appendixes B through G. Three of these latter

solutions were completed in four cycles and the remaining three in three cycles.

TALLYHO, the shortest path algorithm, was run first with the initially defined road network, associated link characteristics, and tonnages of commodities, as input. The resulting output consisted of the routes and their weighted distances, the links and their tonnages and link ton-kilometers, and the objective function in terms of system total ton-kilometers. The value of the objective function here represents the improvement in the minimization of ton-kilometers over the initial network before any investment is made. This output is shown in Appendix A. This output serves as the objective function against which all subsequent solutions (objective functions) are compared to evaluate improvement in level of efficiency.

The output (link flows) obtained from the shortest path algorithm, TALLYHO, served as input to the FRLP model which gave as output the improvement levels in kilometers to which each feasible link was upgraded and the value of the objective function. The value of the objective function here represents the amount of improvement in ton-kilometers over original routes without investment. Output of the FRLP run is given in Appendix A.

The investments determined by FRLP were applied to the road system by changing link characteristics (data) to reflect the improvements. Because these link improvements would result in changes in the pattern of shipping on the various links of the system, TALLYHO was re-run and a new set of routes, link flows, and objective function were obtained.

These results are presented in Appendix A. After making the necessary changes in the link flows, the FRLP was run again with the revised flows and a new set of routes as input, and a set of new investment projects was generated. These investments are shown in Appendix A. Again the value of the objective function represent the maximum reduction in ton-kilometers by making the new investments. When the result obtained in this later solution of FRLP were compared with those obtained in the preceding solution of the FRLP model, no changes in the investments were observed. Therefore, the investments obtained in the last solution of the FRLP represent the final solution to the Sudanese road investment problem under L$100 million budget constraint. Note that the heuristic generated the final solution in this case (of L$100 million budget level) when the investments obtained in two successive applications of the FRLP model are the same. Similarly, the heuristic procedure was applied for Sudanese road network investment problem under other given budget levels and all of the final results are presented in Appendixes B through G.

CHAPTER VIII

ANALYSIS AND EVALUATION OF RESULTS

A summary of the investment sets and their associated minimum total weighted ton-kilometers determined in this study for the Sudanese interregional road network under seven alternative budgets invested in the road work is given in Table 16. The overall objective of each set of road projects generated was to improve the efficiency of the road network system as measured by minimizing total weighted ton-kilometers.

To evaluate the efficiency of each improved network, each final value of the objective function (minimum total weighted ton-kilometers) corresponding to each of the solutions (the investment sets) and its associated improved network were compared to the number of total weighted ton-kilometers over the original network before any investments were made; i.e., compared to 13.06476 billion ton-km. The difference between the two amounts represents the net reduction in weighted ton-kilometers over each improved network. In solution #1 (a budget of L$100 million for road transportation improvement), for example, the final value of objective function of the TALLYHO model (10.00509 billion ton-km.) was subtracted from 13.6476 billion ton-km., and the difference (3.05967 billion ton-km.) represents the amount of net reduction in ton-kilometers over the improved network in comparison to the original one. This amount of reduction is equivalent to 23% and indicates that the level of efficiency, measured in terms of minimum weighted ton-kilometers, of the new improved network is 23% higher than that of the original network.

Table 16

Summary Table of the Model Results

Solution No.	Link No.	Connecting Node Nos.	Road Length Improved (in km.)	Improvement Standard	Project Cost (in L$000's)	Improved Network Total Ton-Km. (in billions)	Net Ton-Km. Reduction (in billions)	% Improvement of Network Efficiency
1	5	3-4	246.0	Earth to Pavement	24,108			
	7	2-5	378.0	Earth to Pavement	37,044			
Budget = L$100 million	9	4-7	315.0	Earth to Pavement	30,870	10.02757	3.03719	23
	12	5-6	39.6	Earth to Gravel	1,872			
	6	2-4	103.0	Gravel to Pavement	6,077			
2	5	3-4	246.0	Earth to Pavement	24,108			
	7	2-5	378.0	Earth to Pavement	37,044			
Budget = L$125 million	9	4-7	315.0	Earth to Pavement	30,870	9.73196	3.33280	26
	12	5-6	560.0	Earth to Gravel	26,880			
	6	2-4	103.0	Gravel to Pavement	6,077			
3	5	3-4	246.0	Earth to Pavement	24,108			
	7	2-5	378.0	Earth to Pavement	37,044			
	11	5-8	331.0	Earth to Pavement	32,438			
Budget = L$150 million	11	5-8	148.0	Gravel to Pavement	8,732	8.98100	4.08376	31
	12	5-6	614.0	Earth to Gravel	29,472			
	12	5-6	123.0	Earth to Pavement	12,054			
	6	2-4	103.0	Gravel to Pavement	6,077			
4	5	3-4	246.0	Earth to Pavement	24,108			
	7	2-5	378.0	Earth to Pavement	37,044			
	11	5-8	331.0	Earth to Pavement	32,438			
Budget = L$175 million	11	5-8	148.0	Gravel to Pavement	8,748	8.67280	4.39196	34
	12	5-6	114.0	Earth to Gravel	5,472			
	12	5-6	623.0	Earth to Pavement	61,054			
	6	2-4	103.0	Gravel to Pavement	6,077			
5	1	1-2	143.6	Earth to Gravel	6,864			
	1	1-2	126.0	Earth to Pavement	12,348			
	5	3-4	246.0	Earth to Pavement	24,108			
Budget = L$200 million	7	2-5	378.0	Earth to Pavement	37,044	8.51196	4.55280	35
	11	5-8	331.0	Earth to Pavement	32,438			
	11	5-8	148.0	Gravel to Pavement	8,742			
	12	5-6	738.0	Earth to Pavement	72,324			
	6	2-4	103.0	Gravel to Pavement	6,077			
6	1	1-2	261.0	Earth to Gravel	12,528			
	1	1-2	8.9	Earth to Pavement	882			
	5	3-4	246.0	Earth to Pavement	24,108			
	7	2-5	378.0	Earth to Pavement	37,044			
Budget = L$225 million	9	4-7	315.0	Earth to Pavement	30,870	8.34190	4.72286	36
	11	5-8	331.0	Earth to Pavement	32,438			
	11	5-8	148.0	Gravel to Pavement	8,742			
	12	5-6	738.0	Earth to Pavement	72,324			
	6	2-4	103.0	Gravel to Pavement	6,077			
7	1	1-2	42.0	Earth to Gravel	2,016			
	5	3-4	246.0	Earth to Pavement	24,108			
	7	2-5	378.0	Earth to Pavement	37,044			
	9	4-7	315.0	Earth to Pavement	30,870			
Budget = L$250 million	11	5-8	331.0	Earth to Pavement	32,438	8.23290	4.83186	37
	11	5-8	148.0	Gravel to Pavement	8,742			
	12	5-6	738.0	Earth to Pavement	72,324			
	15	7-9	758.0	Earth to Gravel	36,384			
	6	2-4	103.0	Gravel to Pavement	6,077			

Note: Total ton-km. of original network before improvement = 13,06478 billion.

Similarly, the increase in level of efficiency for each improved network obtained in other six solutions in the study were calculated. The figures derived were converted into percentages and they are shown in Table 16. The percent increase in efficiency for all improved networks as can be seen from Table 16 ranges from 23% to 37% of total weighted ton-kilometers over original network. In terms of the objective function, therefore, each of the investment sets resulted in an improved network that is considerably more efficient than the actual one. The structural differences between the actual road network before any improvements are made and improved network after investing L$250 million can be seen by comparing Figure 13 and Figure 14 to each other.

Examination of the objective function for all solutions reveals that the decrease in weighted ton-kilometers (and hence the increase in efficiency) over all network simulations tends to rise with every increase in amount of capital invested. The rate of decrease in objective function, however, is not constant but, rather, varies from each level of investment to another, tending to increase at a decreasing rate at higher investment levels. Figure 15 is drawn to demonstrate this relationship between weighted ton-kilometers (i.e., the objective function) and the amount of capital invested in road improvement projects.

Figure 15 shows a tradeoff curve of weighted ton-kilometer improvement as a function of investment. The number of weighted ton-kilometers decreases significantly as the amount of invested capital is increased, suggesting, therefore, a strong negative relationship between the two measures.

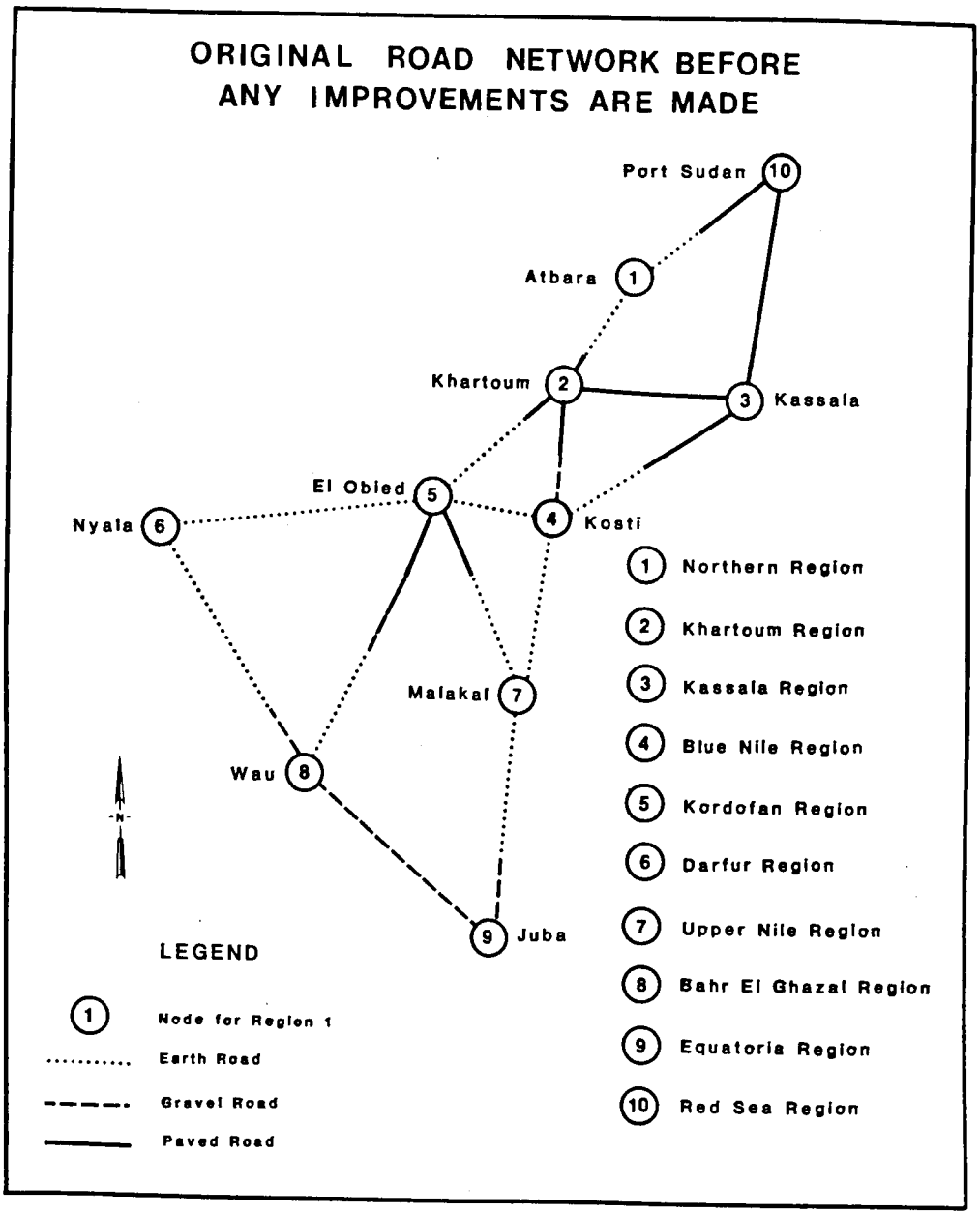


Figure 13. Original road network before any improvements are made.

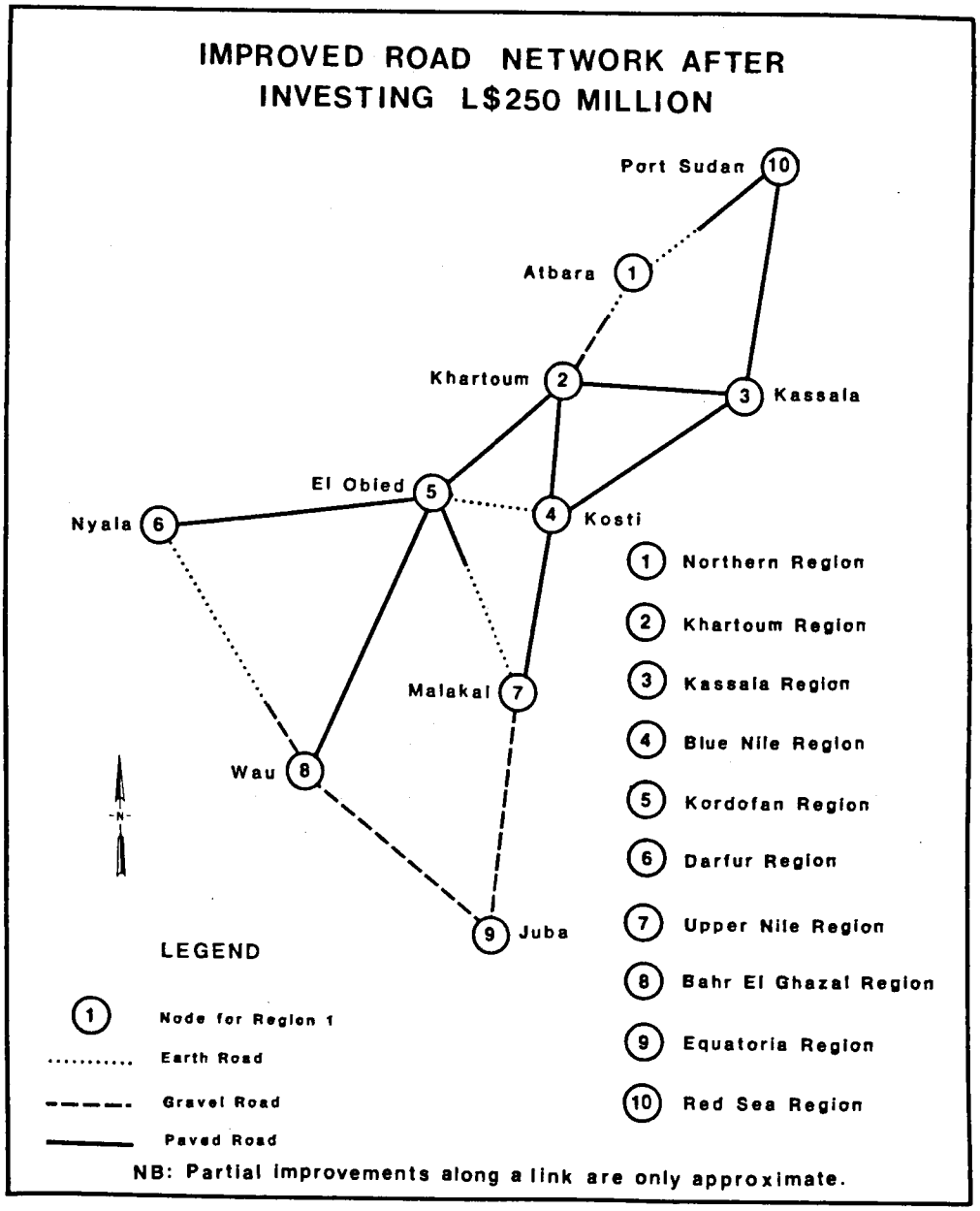


Figure 14. Improved road network after investing L$250 million.

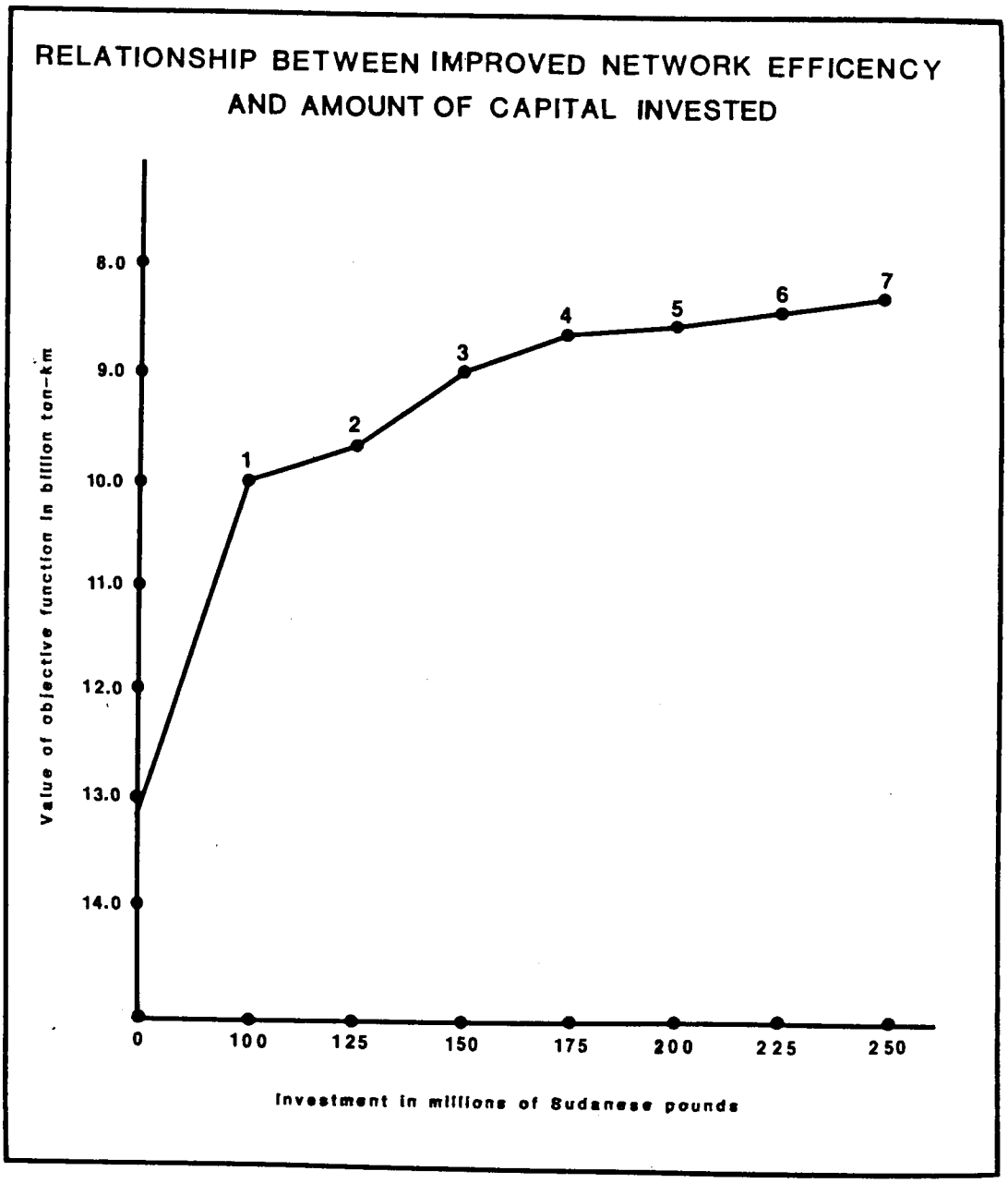


Figure 15. Relationship between improved network efficiency and amount of capital invested.

The initial investment program obtained in solution #1, under L$100 million budget level contributed sizeable decrease to the value of the objective function by reducing total ton-kilometers over the improved network to 10.02757 from 13.06476 billion ton-km., a 23% improvement in level of service efficiency of the improved network compared to that of original network. The initial program set includes improvements in five links. All of link #7 (378 km.) which connects Khartoum and El Obied is upgraded from earth to pavement. All link #9 (315 km.) which connects Kosti and Malakal is upgraded from earth to pavement. The remaining portion of link #5 that is earth (246 km.) and link #6 that is gravel (103 km.) are both upgraded to pavement; thus providing all paved road arteries connecting each of Kassala and Kosti, and Khartoum and Kosti, respectively. Finally the program includes link #12 which connects El Obied and Nyala and this is improved by upgrading only 40 km. of its total length (732 km.) from earth to gravel. These link improvements are shown in Figure 16.

The next value of objective function which is 9.73196 billion ton-km. indicates further improvement in efficiency level (26%) due to improvements in the links made possible by investing L$125 million. This improvement in efficiency is gained specifically by making similar improvements to the same links undertaken in the preceding program except the Nyala-El Obied connection (#12) for which the number of kilometers upgraded jumped from 40 to 560 km. Note that the increase of capital invested from L$100 to L$125 million has increased efficiency level by only 3%.

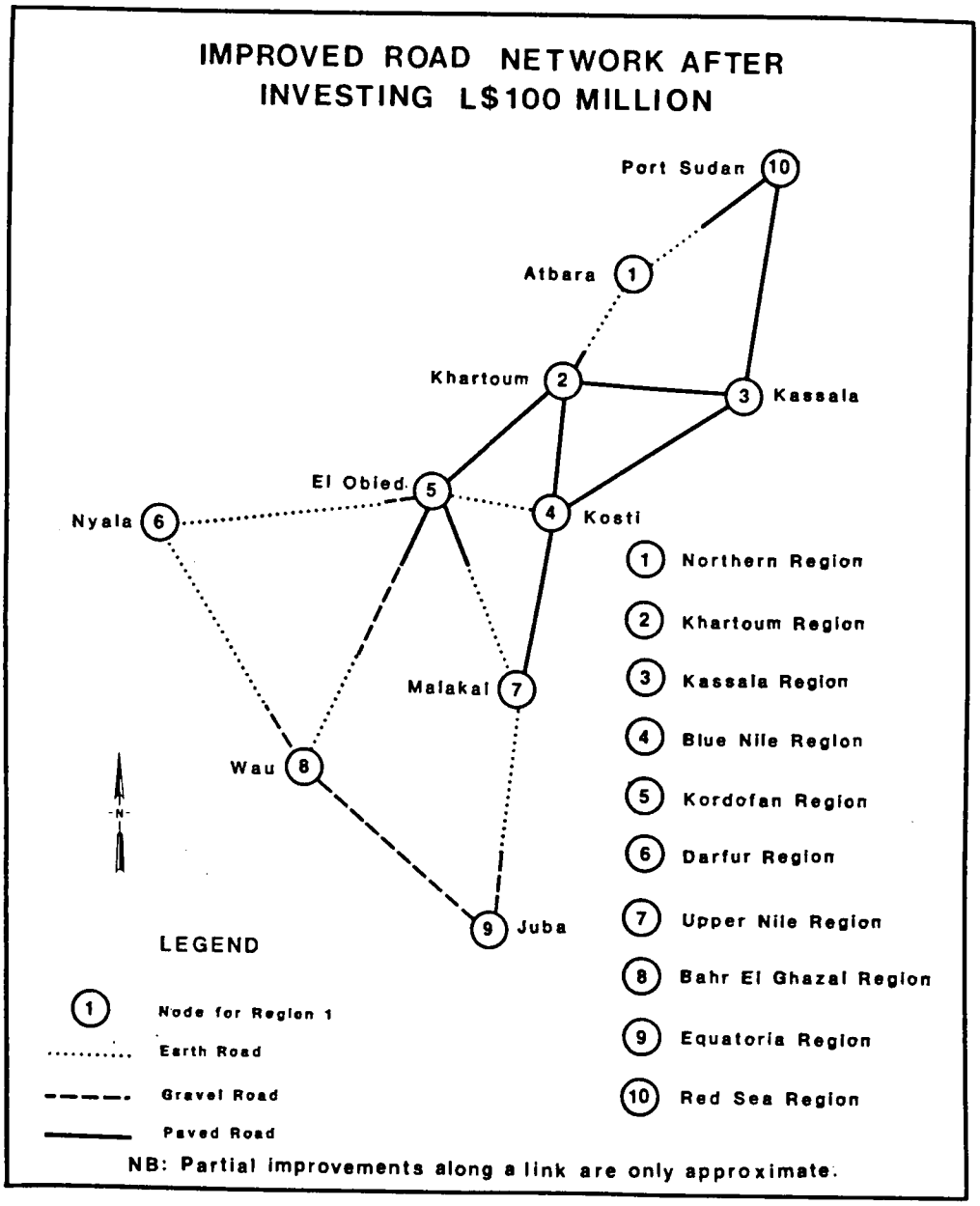


Figure 16. Improved road network after investing L$100 million.

By investing L$150 million, the analysis shows that the value of the objective function is reduced considerably to reach 8.981 billion ton-km., the second largest decrease in the objective function compared to other values obtained in all solutions. This decrement, which is 0.75096 billion ton-km., is second only to the decrement of 3.03719 billion ton-km. obtained in solution #1. The new network efficiency level is increased, therefore, by 31% over that of the original network and by almost 5% over the network obtained in solution #2. The decrement in objective function occurred not only when El Obied-Wau connection (#11) replaced the Kosti-Malakal linkage (#9) and the whole link (i.e., El Obied-Wau) was improved by upgrading its earth portion (331 km.) and gravel portion (148 km.) to pavement standard, but also after improvement of El Obied-Nyala connection (#12). That improvement is accomplished by upgrading 614 km. of its total length from earth to gravel and the rest (123 km.) to pavement.

Likewise, the objective function value obtained in the next four solutions, #4, 5, 6, and 7, continued to decrease steadily (indicating steady increase in network efficiency) every time the capital invested is increased as shown in the figure. By replacing the Kosti-Malakal link with El Obied-Wau link at the L$150 million level of expenditure, an efficiency level that is 6% higher than the level in the preceding improved network (L$125 million) is obtained. It is apparent that the gains associated with linking up El Obied-Wau first emerge as greater than the immediate gains to be achieved by improving the Kosti-Malakal connection, provided that all of El Obied-Nyala section is upgraded to a

higher standard of gravel or pavement. Similarly, the Khartoum-Atbara link (#1) appears in solution #5 (200 million budget) but the amount of improved kilometers of the link is reduced after the Kosti-Malakal connection (#9) is reconsidered for improvement in solution #6 (225 million). Again, the number of improved kilometers of the same link (#1) is further diminished and the link is almost removed from the investment set when both the Kosti-Malakal and Malakal-Juba links are incorporated in the next solution #7. It has become clear in this case, as in the previous case of shuffling the El Obied-Wau and Kosti-Malakal links, that the Khartoum-Atbara connection cannot compete with the value obtained by adding either or both the Kosti-Malakal and the Malakal-Juba links. The Khartoum-Atbara link and the Malakal-Juba link (which was selected for improvement only in solution #7 at 250 million budget level) are both outliers in the network system considered in the study. The inability of the Khartoum-Atbara link to compete with either or both the Kosti-Malakal and Malakal-Juba, however, could be explained by the fact that the Northern region is less densely populated and is, in general, of very limited agricultural and resource potential compared to the Southern region. It is not clear whether all of the Khartoum-Atbara link is potentially viable for improvement at levels of investment higher than the ones considered in this analysis. Further investigation to test for this is perhaps needed. The Northern region is generally not attractive in terms of its economic potential and its present state of development does not warrant a paved road to link it to Port Sudan or Khartoum.

From the preceding discussion of the investment pattern generated by the model, it is apparent that there is some spatial discrimination in the process of network link improvement: efficient road improvements to meet this future demand scenario has not resulted in a great improvement in equality among the regions of the Sudan. The model developed here is not a continuously dynamic one and cannot, therefore, be used to optimally determine the temporal sequence of road improvements. Given the reasonably short planning horizon for which commodity movements have been forecast, however, the linkage improvements determined at each budget level can be compared to indicate a probable construction sequence of planned road upgrades. If the planning horizon were longer, the shifting patterns of interregional demand spurred by the impact of differential road improvements not accounted for in this static model would make any attempt at specifying a temporal sequence of road upgrades suspect.

According to the results of this model application, if the Khartoum-El Obied connection is paved first, then the improvement of El Obied-Nyala link should precede that of El Obied-Wau and/or the Kosti-Malakal links. The connection of El Obied-Wau should precede the improvement of Kosti-Malakal, provided that the El Obied-Nyala link is already upgraded. Then the connections of either or both of the El Obied-Wau and the Malakal-Juba links follow. The improvement of both these latter two links should precede that of the Khartoum-Atbara outlier. From this shuffling of investment priorities and associated link connections emerges a coherent improved network where the regions

of Western Sudan (Kordofan and Darfur), Southern Sudan (Bahr El Ghazal, Upper Nile, Equatoria) and Northern Sudan are connected, in that order of priority, to the rest of the country.

Beyond the L$150 million budget limit invested in the interregional network it has been found that the rate of decrease in ton-kilometers (i.e., decrement in objective function) started to decline gradually in a successive fashion as the amount of money invested is increased. This relationship is illustrated by plotting the decrements in objective functions against investment levels as shown in Figure 17. Note the downward curvature and how it begins to taper off and flatten over the range of the four highest values of capital invested, implying that the marginal return to improvements started to flatten out at higher levels of capital expenditure. This decline suggests that the network may be approaching a point of improvement saturation with respect to its present geometry beyond which more interregional road investments may not be needed. It might, therefore, be more economically viable to invest the budget allocated for transportation improvements in other transportation modes or in intraregional roads.

The process of determining the investments in the present model is very much guided by the final sum of accumulated tonnage (ton load) gained by each link. These tonnages are generated by the model solutions for each link in the network (see Appendixes). Examination of these tonnages give some insight into the relative importance of each improved link and its contribution to network efficiency over all levels of capital invested, and can, therefore, be valuable in ranking the

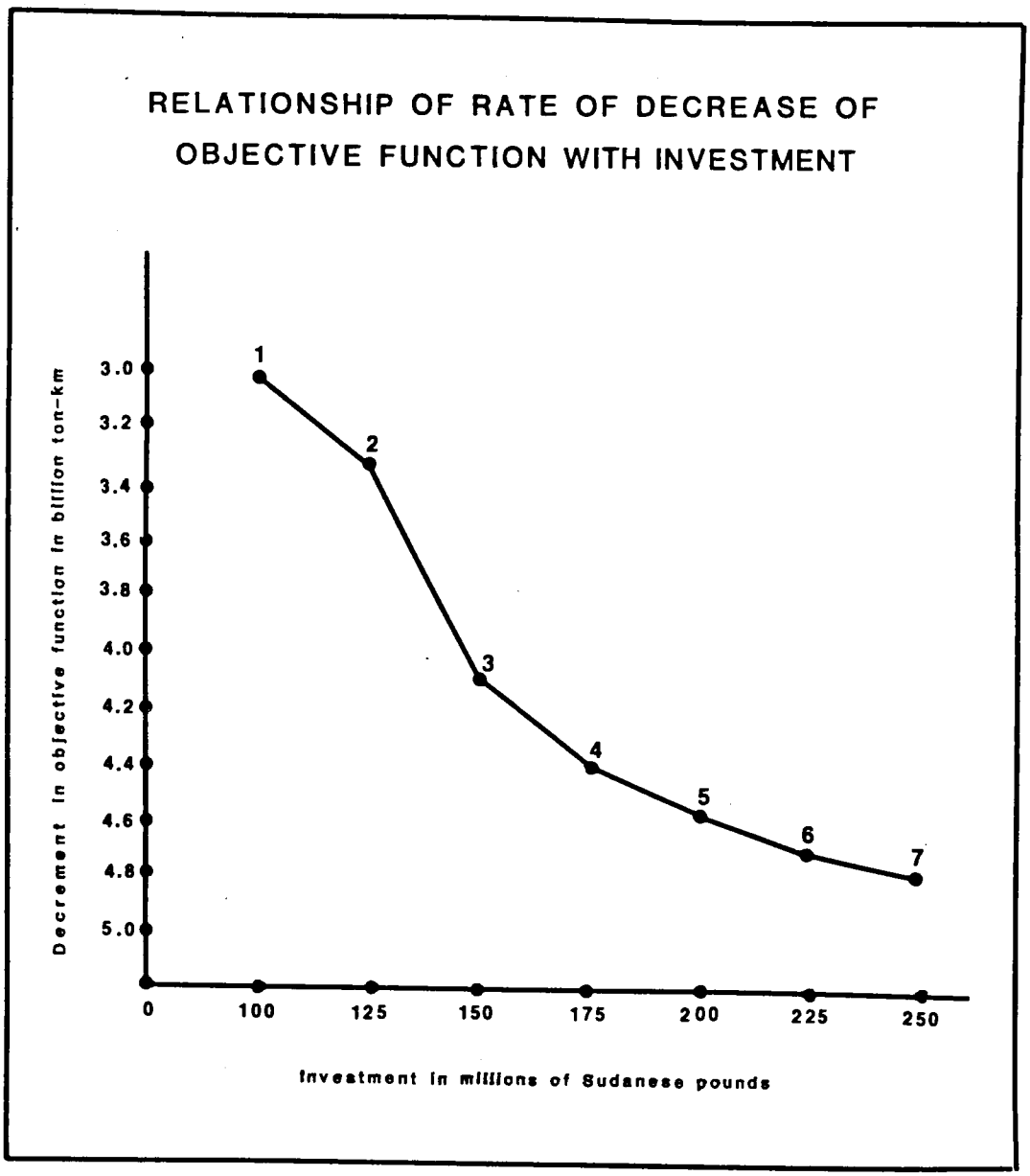


Figure 17. Relationship of rate of decrease of objective function with investment.

investment projects despite the static nature of the interrelationship between road improvements and interregional demands assumed in this model.

A comparison of these tonnages for all improved links reveals that links #5 and #7 have, for example, recorded the highest ton load in comparison to the original distribution of tonnages over the original network. The contribution of these two links alone to network efficiencies range from 28% to 43% of total network efficiency (obtained in solution #1), respectively to 21% and 27% (in solution #7). The change in percent contribution noted here is due to effect of the optimization process and improvements in other links. The percentage contribution to efficiency accounted for by the two links is, however, the highest among all others in the study. These two road links, Kassala-Kosti (#5) and Khartoum-El Obied (#7), appear to be the mainstay of the whole improved network system.

Similarly, when the contribution of other links to the level of efficiency is calculated, the rank order of the improved links is as follows: Kassala-Kosti (link #5), Khartoum-El Obied (#7), Khartoum-Kosti (#6), Kosti-Malakal (#9), El Obied-Nyala (#12), El Obied-Wau (#11), Malakal-Juba (#15), and Khartoum-Atbara (#1).

General Evaluation of Results

The results of the model application reflect a pattern of improvement that is clearly attracted to the central belt of the network where the regions of Khartoum, Blue Nile, Kassala, and Kordofan, the most

densely populated and productive regions in the country, are located. They are also the regions where the concentration of specialized economic activities (industrial and/or agricultural) provides a strong base for complementarity (see Chapters III and IV). Interestingly, the Kosti-El Obied linkage has not been selected for any improvement in the model's solutions. This is not anticipated, but it could be explained partly by the similarity in the product mix of the Blue Nile and Kordofan regions (i.e., lack of complementarity). Both are specialized in the production of almost same types of agricultural crops for export.

An inspection of the map in Figure 14, p. 147, would show that by excluding the Kosti-El Obied link from improvement, the Khartoum-El Obied connection and Kassala-Kosti section (which is part of a paved road artery that reaches Port Sudan) are the most important parallel arterial routes in the improved network components. Along these parallel routes hinge the rest of the improvements generated in the study. The model generated a pattern of improvement in which the Western, Southern, and Northern regions are linked in that order of priority. This order of improvement is found to be a clear response to existing variation in level of economic development and potential economic resources among the regions. Kordofan is, for example, more densely populated and economically advanced than Darfur, Equatoria, Bahr El Ghazal, Upper Nile, or the Northern regions. Alternatively, the Northern region is the most sparsely populated, and poor in economic resources when compared to other regions in the country. It is, therefore, clear that link improvements developed in the model are affected by regional location.

The variation in level of economic development among the regions noted above should be viewed in light of the fact that the national economy of the Sudan is still largely dependent upon foreign trade. Since the pattern of interregional network improvement occurs along two main axes which reach Khartoum and Port Sudan, it is apparent that the improved network generated by the model is oriented towards these two cities. Khartoum and Port Sudan are the two main centers for distribution of import and export products.

Because improvement priority is accorded to the Khartoum-El Obied link, cash crops in Kordofan region, the largest producer of these products in the country, become more accessible to export markets. In comparison to Darfur, or any other region being subsequently linked along the same axis (e.g., Darfur, Bahr El Ghazal), accessibility to the Kordofan region is of primary importance. Similarly, all subsequent links (El Obied-Nyala, El Obied-Wau, Kosti-Malakal, Juba-Malakal, and Khartoum-Atbara) are improved partially or wholly according to the varying requirements of the road transport operations for the movement of commercial products from the regions of Darfur, Bahr El Ghazal, Equatoria, Upper Nile, and Northern, respectively. Link improvements determined by the model are, therefore, largely induced by the import-export trade and the road improvements provide an improved accessibility to the cash crops in the regions.

Finally, the network orientation towards Khartoum and Port Sudan may be perceived as a general one which takes place at a national scale. The Southern region, however, generally shows marked improved network

orientation towards the Kordofan (El Obied) and Blue Nile (Kosti) regions. This is clearly shown when the pattern of investment over solutions obtained at investment levels below L$225 million is examined. This orientation appears split between the Wau-El Obied and Malakal-Kosti road axes with orientation weaker in the direction of the Blue Nile region than the Kordofan region, despite the development advantage that the former has over the latter. Interestingly, this weak orientation of the Southern region towards the Blue Nile region at low investment levels is coincident with the difficult natural conditions that prevail in the Southern region generally and the Upper Nile in particular. The existence of the Sudd, a large swamp area in the Upper Nile region constitutes a physical impedance factor to the road improvement in the region and this can preclude the Upper Nile region, and perhaps, the whole Southern region from being linked either directly to the Blue Nile region or to the Northeast regions of the Sudan (Kassala, Khartoum, and Red Sea) via the Blue Nile region. The orientation of the Upper Nile region towards the Blue Nile region appears stronger, however, after the Kosti-Malakal link is selected for improvement at a high level of capital investment, L$225 million and possibly more.

Some Concluding Remarks

On the basis of the sensitivity of road improvements to capital investment levels, solution #4 with a budget level of L$175 million appears to be the most cost effective, if we measure effectiveness by the reduction in total weighted ton-kilometers (i.e., increase in

network efficiency) and the cost of the investment as the capital invested (see Figure 14, p. 147). At a L$175 million level of capital investment the tradeoff of capital cost for network efficiency is much higher than at any of the subsequently higher levels of capital investment. Given the scarcity of available capital in the Sudan and/or any reduction in the L$250 million budget proposed for road works in the Six-Year Plan 1977-1983, it is likely that the Sudanese government would desire to invest at least L$175 million in road improvement. The program obtained in solution #4 maintains an efficiency level that is 34% higher than that of the original unimproved network. Rather than to spend an additional L$75 million (i.e., invest L$250 million) and reap additional benefits of only 3% of increased network efficiency, scarce development resources might be better spent for other transportation modes or at a different scale of resolution (e.g., intraregional feeder roads). The configuration of the improved network obtained with a budget expenditure of L$175 million is shown in Figure 18 and can be compared to the improved network under L$250 million shown in Figure 14. The system of improved roads have been established by solving an investment model designed to determine optimal improvements in inter-regional road network of the Sudan. The model provides an improved network that satisfies the fixed demand placed on it by the shippers and concomitantly minimizes total weighted ton-kilometers encompassed by the objective function. The resulting improved network maintained an efficiency level that is significantly higher than that of the original unimproved network (see Table 16, p. 144). The investment program

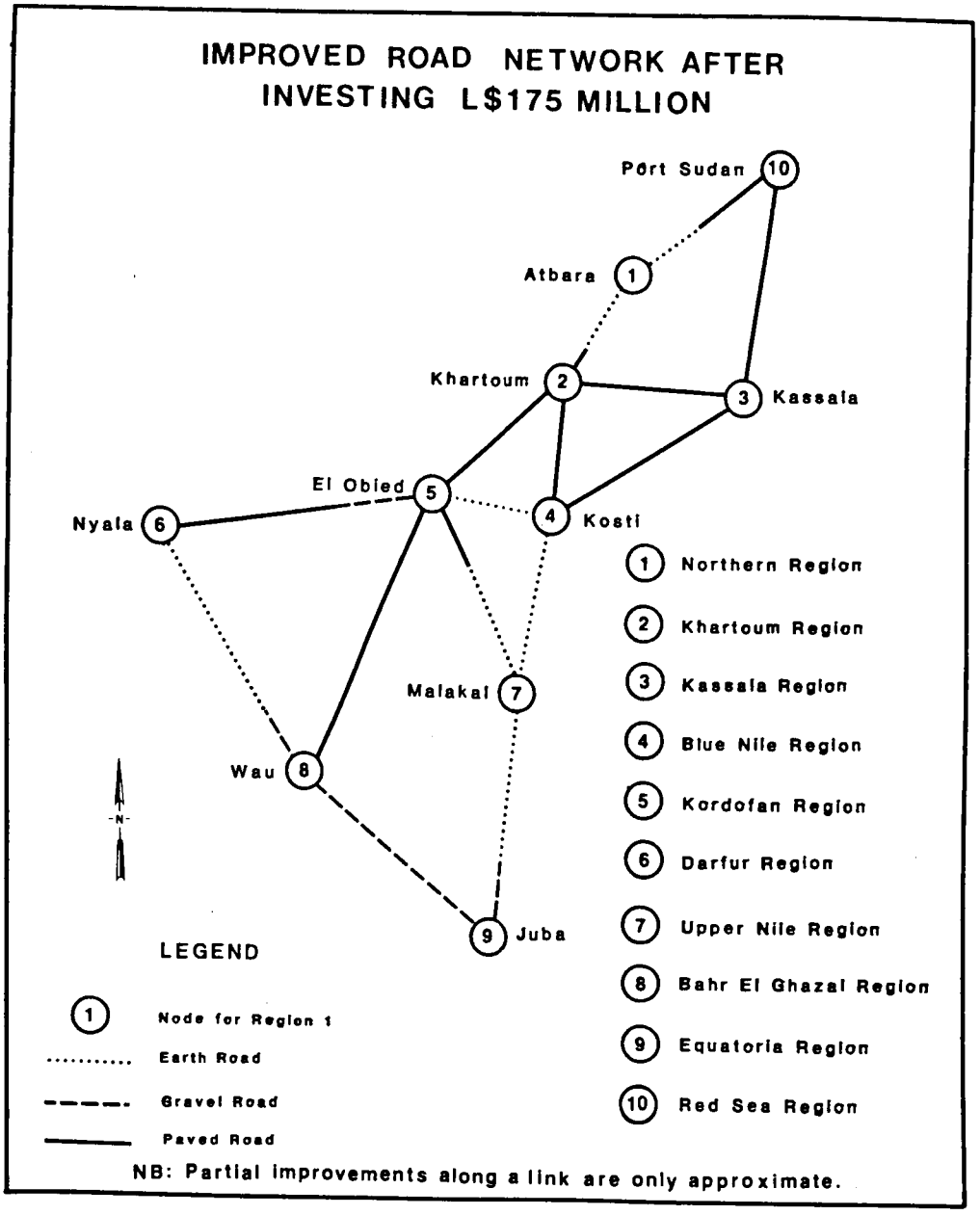


Figure 18. Improved road network after investing L$175 million.

specified by the model can be justified on the basis of its contribution to overall efficiency of the network and increased accessibility to cash crops in each region. The investment program and each improved link therein could also be justified on the basis of its contribution to other specific regional and national strategic development needs, the subject of the next chapter.

Since investments were determined in terms of number of kilometers of a link which need to be upgraded, it has been possible to use these values with the known per-kilometer cost of improving roads at different standards to calculate total upgrading cost for individual link projects in the program. (These costs are shown in Table 16.) On the basis of these project costs and the established link improvement values, it would be easy to phase the selected program for implementation. The program can, therefore, be implemented as a whole or phased into stages depending on how much investment capital could be made available. While the implementation of the plan could be done in stages, the investment in each stage should be thought of as part of a complimentary set of investments which in total is designed primarily to raise the efficiency and improve the level of service of the whole road transportation system in the country.

The model used in this study was solved heuristically. The solutions, and hence the investments, generated by the model, may or may not, therefore, be exactly optimal. As with most heuristic approaches to combinatorial problems, it is very difficult, if possible at all, to

determine the degree to which results may deviate from optimality (43). In the following section, however, an attempt is made to measure the departure of the model results from optimality and to evaluate the performance of the cyclic heuristic in generating solutions of the model used in the study.

Evaluation of the Heuristic Method of Solution

To determine the degree to which each solution obtained by the heuristic method is at variance, if at all, with the true optimal solution, one needs to compute a lower bound on the optimal solution. The approach adopted to generate the bounds was based upon transforming the original nonlinear model (displayed in Chapter VI) into an equivalent integer programming model which is solvable optimally by using the branch-and-bound technique and then solving this new formulation by linear programming. The linear programming solution, in this case, will always produce the lowest possible values of objective function, and can, therefore, be used to represent the required lower bounds. This approach to generating lower bounds to the solutions of the heuristic model can be operationalized. The linear programming solution of the integer model represents lower bound on the optimal integer solution, and, therefore, to the heuristic model solution as well. The relationship among value of the objective function in the linear programming solution (which may be fractional), the optimal integer solutions of the integer model, and the heuristic solution can be expressed by the following equation:

Linear programming solution ≤ optimal integer solution ≤ heuristic solution,

which implies that the optimal solution lies somewhere between the linear programming solution (lower bound) and the heuristic solution.

The equivalent formulation of the investment model consists of a basic integer model which, after being modified, led to a large integer programming model. The basic integer formulation is given below.

Let EP_{uv} = number of kilometers of road segment (u,v) that are improved from earth to pavement

EG_{uv} = number of kilometers of road segment (u,v) that are improved from earth to gravel

GP_{uv} = number of kilometers of road segment (u,v) that are improved from gravel to pavement

X_{ij}^{r} = | 1 if the rth route from i to j is used for shipments between i and j
| 0 otherwise

T_{ij} = the amount of tons that are to be shipped between region i and region j during the planning period

D_{ij}^{r} = the current "weighted" distance of the rth route between i and j before investments

w_e = weight attached to ease of travel (i.e., travel cost) on earth road segments

w_g = weight attached to ease of travel on gravel road segments

w_p = weight attached to ease of travel on paved road segments

ϕ = the set of node pairs (i,j)

$n(i,j)$ = the number of routes between region i and region j

C_{ep} = per-kilometer cost of upgrading earth to pavement

C_{eg} = per-kilometer cost of upgrading earth to gravel

C_{gp} = per-kilometer cost of upgrading gravel to pavement

B = total budget allocated to road work

e' = number of kilometers of link (u,v) that are earth before investment

g' = number of kilometers of link (u,v) that are gravel before investment

DP_{ij}^{r} = the number of kilometers of route r between node pair (i,j) that have been improved from earth to pavement and are used toward improving weighted distance. This is limited by:

(1) the amount of use the rth route is actually assigned, i.e., X_{ij}^{r}

(2) the actual improvements on the links of the rth route from earth to pavement

DR_{ij}^{r} = similar variable as DP_{ij}^{r} except that DR_{ij}^{r} deals with earth to gravel improvements

RP_{ij}^{r} = similar variable as DP_{ij}^{r} except that RP_{ij}^{r} deals with gravel to pavement improvements

D_{ij}^{rg} = current gravel kilometers on the rth route between i and j before investment

D_{ij}^{re} = current earth kilometers on the rth route between i and j before investment

$$\text{Minimize} \quad \sum_{(i,j)\in\phi} \sum_{r=1}^{n(i,j)} T_{ij}\, D_{ij}^{r}\, X_{ij}^{r}$$

$$-(w_e - w_p) \sum_{(i,j)\in\phi} \sum_{r=1}^{n(i,j)} T_{ij}\, DP_{ij}^{r}$$

$$-(w_e - w_g) \sum_{(i,j)\in\phi} \sum_{r=1}^{n(i,j)} T_{ij}\, DR_{ij}^{r}$$

$$-(w_g - w_p) \sum_{(i,j)\in\phi} \sum_{r=1}^{n(i,j)} T_{ij}\, RP_{ij}^{r}$$

Subject to

(1) $\sum_{r=1}^{n(i,j)} X_{ij}^{r} = 1$ for each $(i,j)\in\phi$

(2) $RP_{ij}^{r} \leq D_{ij}^{rg} \cdot X_{ij}^{r}$

(3) $DP_{ij}^{r} + DR_{ij}^{r} \leq D_{ij}^{re} \cdot X_{ij}^{r}$

(4) $DP_{ij}^{r} \leq \sum_{(u,v)\in R_{ij}^{r}} EP_{u,v}$

(5) $RP_{ij}^{r} \leq \sum_{(u,v)\in R_{ij}^{r}} GP_{u,v}$

(6) $DR_{ij}^{r} \leq \sum_{(u,v)\in R_{ij}^{r}} EG_{u,v}$

(7) $EP_{uv} + EG_{uv} \leq e'_{uv}$

(8) $GP_{uv} \leq g'_{uv}$

(9) $X_{ij}^{r} = 0$ or 1 for all ij and all routes between i and j

$$(10) \quad \sum_{(u,v)\in A} C_{ep}\, EP_{uv} + C_{gp}\, GP_{uv} + C_{eg}\, EG_{uv} \leq B$$

The following three constraints also need to be inserted to prevent counting improvements on routes between a given node pair that total more than the sum of all improvements on all links of those routes.

$$(11) \quad \sum_{r=1}^{n(i,j)} DP_{ij}^{r} \leq \sum_{(u,v)\in AR_{ij}} EP_{uv}$$

$$(12) \quad \sum_{r=1}^{n(i,j)} DR_{ij}^{r} \leq \sum_{(u,v)\in AR_{ij}} EG_{uv}$$

$$(13) \quad \sum_{r=1}^{n(i,j)} RP_{ij}^{r} \leq \sum_{(u,v)\in AR_{ij}} GP_{uv}$$

where,

AR_{ij} = the set of links used by all routes between i and j.

When the above model was solved by linear programming, the results achieved were unsatisfactory in that the bounds were not sufficiently high to allow evaluation of the heuristic model solutions.* Further modifications were, therefore, performed in this basic integer model in order to improve the bounds. The modified version of the integer model is given below:

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*For example, lower bound in a solution obtained at L$125 million budget level was 6.600 billion ton-km.; whereas the cyclic heuristic generated 9.7 billion ton-km.

$$\text{Minimize} \quad \sum_{(i,j)\in\phi} \sum_{r=1}^{n(i,j)} T_{ij}\, D_{ij}^{r}\, X_{ij}^{r}$$

$$-(w_e - w_p) \sum_{(i,j)\in\phi} \sum_{r=1}^{n(i,j)} \sum_{(u,v,)\in R_{ij}^{r}} T_{ij}\, DP_{ij}^{r-u,v}$$

$$-(w_e - w_g) \sum_{(i,j)\in\phi} \sum_{r=1}^{n(i,j)} \sum_{(u,v)\in R_{ij}^{r}} T_{ij}\, DR_{ij}^{r-u,v}$$

$$-(w_g - w_p) \sum_{(i,j)\in\phi} \sum_{r=1}^{n(i,j)} \sum_{(u,v)\in R_{ij}^{r}} T_{ij}\, RP_{ij}^{r-u,v}$$

Subject to

(1) $\sum_{r=1}^{n(i,j)} X_{ij}^{r} = 1$ for each $(i,j)\in\phi$

(2) $RP_{ij}^{r-u,v} \leq g'_{uv} \cdot X_{ij}^{r}$ for each link (u,v) on the rth route that has gravel

(3) $DP_{ij}^{r-u,v} + DR_{ij}^{r-u,v} \leq e'_{uv} \cdot X_{ij}^{r}$ for each link (u,v) on the rth route that has earth

(4) $DP_{ij}^{r-u,v} \leq EP_{uv}$

(5) $RP_{ij}^{r-u,v} \leq GP_{uv}$

(6) $DR_{ij}^{r-u,v} \leq EG_{uv}$

(7) $\sum_{r=1}^{n(i,j)} \sum_{(u,v)\in R_{ij}^{r}} DP^{r-u,v} \leq \sum_{(u,v)\in AR_{ij}} EP_{uv}$

(8) $\sum_{r=1}^{n(i,j)} \sum_{(u,v)\in R_{ij}^{r}} DR_{ij}^{r-u,v} \leq \sum_{(u,v)\in AR_{ij}} EG_{uv}$

$$(9)\quad \sum_{r=1}^{n(i,j)} \sum_{(u,v)\epsilon R_{ij}^{r}} RP_{ij}^{r-u,v} \leq \sum_{(u,v)\epsilon AR_{ij}} GP_{uv}$$

$$(10)\quad EP_{uv} + EG_{uv} \leq e'_{uv}$$

$$(11)\quad GP_{uv} \leq g'_{uv}$$

$$(12)\quad \sum_{(u,v)\epsilon A} C_{ep}\, EP_{uv} + C_{gp}\, GP_{uv} + C_{eg}\, EG_{uv} \leq B$$

$$(13)\quad X_{ij}^{r} = 0 \text{ or } 1 \text{ for all ij and all routes between i and j}$$

where

$$DP_{ij}^{r-u,v},\ DR_{ij}^{r-uv},\ \text{and}\ RP_{ij}^{r,u,v}$$

are the same type of variables found in the previous basic formulation except that they deal with the individual links (u,v) on the rth route. That is there is one variable for each u,v on the rth route rather than one variable for each route for a given city pair. R_{ij} = the set of links (u,v) in the rth route between i and j.

The structure of this modified integer programming model is similar to the previous basic integer formulation. The basic difference between them, however, is that the constraints in the basic model were based upon route flows between node pairs whereas the constraints in the modified version deal with link flows.

A program called "FOXBAT" was written to allow the integer model to be solved by linear programming, using MPSX. When the modified integer model was solved it yielded linear programming solutions (i.e., fractional solutions) which represent substantially improved lower bounds in comparison to the previous basic formulation. These linear

programming solutions are, therefore, considered in the following analysis as the lower bounds with which the heuristic model results are compared.

The objective function values (in ton-kilometers) obtained in the previous seven heuristic solutions of the original model are compared to the lower bounds of the globally optimal integer solutions in Table 17.* The percent deviation of each solution from its corresponding lower bound is computed; these percentages are also shown in the table. As indicated by these figures, all the heuristic solutions (i.e., objective function values) are within a range of 2.9 to 7.5% from the lower bounds of optimal integer solutions. Since the optimal integer solutions lie between these lower bounds and the heuristic solutions it becomes clear that the heuristic solutions, if not exactly equal to the optimal, are certainly close to it. On the basis of these results, therefore, it could be concluded that the quality of the nonlinear model (i.e., heuristic) solutions is excellent, differing, if at all, from optimality by only a very small percentage.

In order to evaluate the computational efficiency of the heuristic method, the number of iterations and computer time (CPU) taken by each of the seven solutions sought are examined. By way of comparison, each linear programming solution of the integer formulation required over 2 minutes, on the average, of CPU time and over 800 iterations to

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*The lower bounds on weighted ton-kilometers in this case are not feasible investments; therefore, the bounds do not represent feasible solutions.

Table 17

Deviation of Heuristic Model Results from Optimality

Solution No.	Capital Invested (in million Sudanese pounds)	Objective Function of Heuristic Model (in billion ton-km.)	Objective Function of Integer Model-Linear Programming Bound (in billion ton-km.)	% Deviation of Heuristic Solution from Lower LP Bounds
1	100	10.02757	9.41281	6.5
2	125	9.73196	9.04648	7.5
3	150	8.98100	8.72698	2.9
4	175	8.67280	8.43870	2.7
5	200	8.51196	8.18929	3.9
6	225	8.34190	7.95319	4.8
7	250	8.23290	7.74628	6.2

converge on the solution; whereas each of the heuristic solutions was obtained on the average, after less than half a minute and 18 iterations counted over all cycles of the solution. The times for the heuristic solutions are, therefore, substantially shorter than for the integer programming solutions, clearly indicating the efficiency of the cyclic heuristic method. Note that the CPU time in case of the integer solution approach is calculated for the linear programming solution which is a fractional infeasible solution to the integer model. It would, however, require excessively higher computation times to generate the optimal integer solution by using branch-and-bound technique. Such a high computation time would be a deterrent to the use of integer approach in situations like the present one, and alternatively, therefore, provides a clearcut justification for using the heuristic method.

As noted previously, the number of cycles needed to converge on each of the heuristic solutions was usually 2 to 3, and never more than 4; the number of iterations to find a solution in each cycle was generally less than 11. These results indicate stability that is worthy of further study. Given the size of the present road investment problem, 10 nodes and 15 links, the cyclic heuristic method proved to be successful in generating robust solutions and has proved to have an immediate practical use for the assessment of road development projects especially for developing countries. It would be useful to apply the heuristic to somewhat larger network problems to further confirm the viability of the method and to determine if this robustness of solutions prevails.

CHAPTER IX

SOCIOECONOMIC AND POLICY IMPLICATIONS OF MODELED ROAD IMPROVEMENT IN THE SUDAN

The purpose of this chapter is to identify and evaluate some socioeconomic and policy implications of road link improvements determined in this study for the regional and national development of the Sudan. The socioeconomic impacts will be discussed in a general way first, with reference only to improvements determined in this study. Then a complementary analysis of the benefits that might be set in motion as a result of road transportation improvement will follow. Policy implications will be discussed in the third section of this chapter.

Possible Effects of Modeled Road Link Improvements

Although the model does not recommend upgrading all links to the highest standard (e.g., Juba-Wau), and some have not been upgraded at all (e.g., Kosti-El Obied), there is certainly a greater degree of connectivity among the regions of the Sudan at a considerably higher level of efficiency than prior to investment.

The investment program determined in this study closes the existing gaps in the paved trunk road system connecting the northeastern regions, Khartoum, Blue Nile, Kassala, and the Red Sea, as well as the Western Sudan region of Kordofan. These gaps are bridged by upgrading the Khartoum-Kosti, Kassala-Kosti, and Khartoum-El Obied road sections to

pavement standard. An intensive internal exchange of trade commodities among these relatively specialized regions might be affected by such improvements. Road improvements in these parts of the country are also necessary if the further growth of those dynamic areas is not to be impeded by unsatisfactory traffic conditions. The Kosti-El Obied link between the Blue Nile and Kordofan regions is the only unimproved interconnection among the northeastern regions, as this link remains earth in the model results. The fact that the Kosti-El Obied link remains earth does not imply that the road is of no significance. Under present conditions of the Sudan, the Kosti-El Obied connection appears to be adequate to provide the necessary level of access between the Blue Nile and Kordofan regions.

The extensions of road improvement to the Darfur, Bahr El Ghazal, and Upper Nile regions or to the Western and Southern regions generally are designed to serve planned and existing agricultural schemes, and are needed to open up new production areas in them. The new road improvements may allow the Western and Southern regions to achieve a break with the subsistence economies which are predominant there now. The improved access could allow the gradual emergence of a market economy and increased demand for manufactured and industrial products within these regions. In the case of Darfur and other parts in Western Sudan, for example, the improvement of the El Obied-Nyala connection to a paved surface allows cash crops to be shipped to outside markets, thereby allowing farmers to increase their acreage in production and their incomes. The movement of groundnuts and sesame, for instance, requires

low cost transportation over long distances. These products should acquire more importance in the region when long-haul transport facilities are introduced in the region by the upgrading of the El Obied-Nyala link. Farmers already growing these cash crops could increase their acreage and output and further improve their cash income.

Similarly, improvement of El Obied-Wau and Kosti-Malakal road links to pavement and the Juba-Wau link to a gravel surface are required to serve the expanding plantation and commercial agricultural schemes in the Bahr El Ghazal, Upper Nile and Equatoria regions. These links provide access to the whole Southern region so that penetration of the region from the outside will be increased. In this way the local economy should be stimulated, making it easier to develop heretofore underdeveloped natural resources throughout the whole Southern region. These resources are untapped partly because of lack of good road transportation facilities. The improved connections specified in the model could provide the impetus for change in the Southern region. They should also provide year-round reliable road transportation operations to and from the Equatoria, Upper Nile and Bahr El Ghazal regions. This increased reliability should allow products such as tea, coffee, and perishable fruits, whose development is booming in those regions, to be transported over greater distances (e.g., to Khartoum) in shorter travel times, and with less risk of spoilage in deliveries. In turn, manufactured and industrial products from Khartoum would be more easily moved to the Southern region. The improvement in the El Obied-Wau, Kosti-Malakal, and Wau-Juba links should, therefore, permit local

markets in the Southern region to expand beyond subsistence agriculture and allow wider outside marketing of the region's products, further stimulating development of cash crops in the Southern region as a whole.

The Southern and Darfur regions have remained remote from the centers of development and rather loosely linked with the rest of the Sudanese economy. The regions have been in many ways more connected with their southern (e.g., Uganda) and western (e.g., Chad) neighbors than with the remainder of the Sudan. By improving the El Obied-Nyala and El Obied-Wau links to a paved surface and completing other improvements such as upgrading the Juba-Wau link to gravel, it might be possible to reduce the isolation of the two regions and their population, to promote administrative and political unity, to curb international orientations towards Uganda and Chad, and to integrate both the Southern and Darfur regions more into the mainstream of national development.

Link improvements determined in the study conform to the main direction of interregional commodity flows (described in Chapter VI) indicating that the model merely reflects the nature of the input data. The improved links form the backbone of a national road network which can serve new or improved linkages (e.g., feeder roads) in the future. The improved Khartoum-El Obied-Nyala road artery, for example, makes it feasible to later extend the road to El Fasher, El Nahud or El Gineina, thus integrating those isolated areas in the Western and Central regions.

Benefits of Road Improvement

There are direct and indirect effects of road improvements in the Sudan. The direct effects are quantifiable and are reflected in costs and/or the quality of services provided. Indirect effects are manifested in a variety of ways--economic, political, and social.

Total transportation cost has been reduced by improvements made in the road system. Because of data limitations, it is impossible to compute all costs saved by improvements in the country's road system.

One particular result of improved road transportation in the Sudan is related to vehicle operational period. On the average, the number of operational days per annum for a medium-size truck was found to be 270 days (95). During the rest of the year the trucks could not operate because of rains which make it impossible for trucks to pass through dirt tracks. In rainy periods the annual repair and maintenance of the vehicle is carried out in order to prepare it for next year's operation. With the provision of asphalt road facilities, the average truck operational days in some parts of the country, such as in the north-eastern regions, increased from 270 days to the whole year. As a result truck operators have been able to increase their annual mileage and, therefore, their net revenue.

Aside from the direct effects of road improvements discussed, there are other influences of improved roads that are difficult to quantify which are related to changes in settlements, land use, and agricultural production and structure. The following analysis of impacts of roads

expansion is done in a general way with reference to specific examples where possible.

The effect of transportation delays has proved to be very harmful to external and internal trade in the Sudan. Production needs to be shipped to marketing points at appropriate times to take advantage of market conditions. In the Sudan, railroads often experience delays in delivering products at appropriate times (100). These delays have caused lost market opportunities since exporters usually adjust selling times to the periods of market demand. In some cases exporters were obliged to set long range schedules for the sale of their products because of uncertainty about finding a chance to move their products to the port. They also found themselves subject to financial losses because they were not able to keep to the provisions of purchasing contracts. Also the unreliable transportation service slowed down the discharge of products. As a result, producers found no income to pay their debts to the banks which provided them with the initial loans. Time interest on these loans further increased the debts and, therefore, added more costs to producers, leading to an increased cost of the products. Crops were, furthermore, often spoiled or were infected by insects and diseases. Delays owing to transportation also hampered industrial production. In 1968 large quantities of manufactured food oil were found to be accumulating in storage facilities of some oil mills in Khartoum, waiting to be shipped to the port. Because of this accumulation and lack of storage capacity, the factories reduced their production capacities and threatened to layoff some of their employees (72).

With the provision of modern roads between regions in the central area (Khartoum, Blue Nile, and Kassala) and Port Sudan, most of the problems noted above have been eliminated. Farmers have become more responsive to increased prices facilitated by these modern roads. The improved road service has enabled them to take full advantage of the increase in demand. Time saved, therefore, means more income to producers, economies in inventory, storage space, as well as reduction in credit needs. Paved roads, likewise, lessen losses due to deterioration of perishable goods.

In many parts of the Sudan construction of new roads or the availability of road transportation, has stimulated agricultural production and other economic activities. Changes in land use and in the structure of agricultural production are observed particularly in the area immediately adjacent to new modern roads. A typical example is the Medani-Khartoum highway along which intensive commercial farming has developed and expanded recently. Dairy farming, market gardening, and the cultivation of vegetables are new agricultural activities that had not existed when the road was just earth. Most of these activities are concentrated around Khartoum. New commodities have been brought to Khartoum such as eggs, poultry, fruits and fresh vegetables. The paved road made it possible to move these perishables for which rapid transportation is essential. The new road provides access to two major markets in Khartoum and Medani. Also ribbons of intensive farming similar to the ones along the Khartoum-Medani road are stretching along the three paved roads radiating out of Khartoum connecting Gaili, Jebel Aulia, and

Wadi Sayedna. Spontaneous and organized settlements with a number of available urban services have sprung up along these roads.

Road and rail transportation in the Sudan have both been important agents in promoting urbanization. The growth of townships was at first largely dependent on the location of railways. In recent years, the function formerly performed by the railways has been taken over by trunk roads. Road-link-induced growth of town have become a marked phenomenon in the process of urban development in the Sudan. El Kamlin and El Gaili are notable examples of townships that have grown substantially though they are not located at railroads, but rather on trunk roads. In the case of El Kamlin, for example, the construction of the Medani-Khartoum road provided the needed threshold for small businesses to spring up. In addition, the road has increased mobility for people and goods and given the city's residents access to markets in Khartoum and Medani. Today, many of the residents are engaged in businesses related to dairy farming and market gardening. It is quite possible that El Kamlin may become specialized in these types of economic activities in the future. The new modern roads, therefore, increased the development already started in the areas served by the railway by allowing a larger and more intensive spatial expansion of urban centers away from the railway lines.

The presence of only unimproved roads can retard economic development. In 1969, for example, a development project called the Gerih el Sarha Settlement Scheme was designed and implemented in a predominantly nomadic area in the Kordofan region with the objectives of providing

well planned grazing lands for development, establishing an economic basis for agricultural production in the grazing lands, and settling nomads to enable provision of government services. By 1975, the program had not met its goal. The main cause of the project's failure was the shortage of transportation. The project area is 400 km. from El Obied (the administrative center for the project, and 235 km. from El Fasher, the provincial capital of Darfur). The roads between El Obied and the project area are only suitable for high-speed travel in the dry season, while in rainy conditions they are impassible and the only road is through the region of Darfur, a 912 km. route. It is impossible to administer the scheme from that distance (70).

Because of inadequate transport, producers were obliged in many cases to sell their crops at production sites at prices lower than they might have obtained if they had been able to find the appropriate means to move their products in time and sell them in Port Sudan (72). Inadequate transportation, therefore, results in low prices of products in regions of production which in turn discourages producers from increasing production. Recent construction of modern roads connecting Port Sudan to some of the production areas in the interior has partially solved the problem of crop movement.

The positive effects of even earth transportation on stimulating economic development in some parts of the country cannot be overlooked. In an effort to bring previously unproductive arid land into cultivation, the Sudanese government in the late sixties designed a mechanized farming project (46,000 ha.) for production of cotton in the Abu Irwa

area southeast of Gedaref to supply a nearby textile mill. Although none of the feeder roads were hard-surfaced, they substantially improved the area's access, expanded market opportunities, and made it possible for inputs like fuel and labor to be supplied to farmers without interruption at times of cultivation (70). As a result of these road effects, the pattern and structure of production was completely changed. Cotton production ceased by 1972; the area devoted to the production of sesame and sorghum expanded instead. Cotton is grown in the Sudan as a joint-cost crop (between the government and tenants). The government retains export marketing proceeds of cotton production and gives the tenants a percentage of the net income from the commodity. On the other hand, sesame and sorghum are mostly marketed domestically and tenants obtain the full proceeds of their own production. The lowered transportation cost induced by improvements in road transport in the Abu Irwa project area, encouraged the farmers to shift their activity from growing cotton to sesame and sorghum. Lowered costs enabled them to market their products at places where they were able to obtain high prices for their crops and, thereyby increased their profit and real net income.

In the Western region a small proportion of the villages are located on or near railway lines. Prior to road transport availability, few people ever travelled to the larger towns; crops were poor, and there was little appreciation of the benefits from planting higher yielding crops. Today most of these areas have been linked by dirt roads with the modern economy; lands previously considered uneconomic or

marginal have been cultivated and cash crops have been expanding. Today the Western region alone produces 50% of total production of groundnuts and the crop has replaced gum-arabic as the second largest exported cash crop of the Sudan.

The growth of urbanization and increased domestic migration owe much to improved road transportation services. Of the four major cities in the Darfur region (El Gineina, Nyala, Zalingie, and El Fasher) all but Nyala owe their development to earth road transportation services. Even Nyala owes its emergence as a major urban center to earthen routes which connected it to other towns in and outside the region, prior to its present connection by the railroad. It is estimated that 30 trucks entered Nyala daily before it was reached by railroad (71). El Nahud in Kordofan and Dongola in the Northern region have both become centers of collection for commodities produced in nearby villages and of distribution for consumer products brought from abroad. Thus both have become major cities because each is connected to its respective constellation of villages by a converging nexus of dirt roads. The increased mobility of population and freight in Western Sudan would not have taken place without the availability of such road transport facilities.

Some Policy Implications

The foregoing discussion reveals that improved road transportation in the Sudan has direct impact on the structure of the economy, urban development, national integration and other economic and social developmental aspects of the country. To cater to traffic generated by

future developments in the agricultural and industrial sectors, to provide connection between supply and demand points, to link new production areas to the rest of the country, and to increase the connectivity of the network, are all stated objectives for the development of road transportation in the Sudan. In the present study it has been possible to define optimal or near optimal road transport improvements which minimized total weighted ton-kilometers on the basis of relative travel time so that the overall interregional road transport system efficiency is improved.

The long-run policy in the Sudan is directed toward further expansion of the road system. As of yet this policy is not clear on many issues such as building main trunk roads versus feeder roads and investing in already developed versus backward regions. The current policy appears to be one of building up the main road system first and later attending to feeder road improvement.

The present and planned system of paved feeder and main road projects have been so far almost exclusively undertaken in the Blue Nile, Kassala, and Khartoum regions. This system comprises more than 2,508 km. The only exception to this concentration of activity in the northeast is the Nyala-Kas-Zalingie road project in Darfur and the Debeibat-Dilling-Kadugli road project in the Kordofan region. The 400 km. of feeder roads provided for in the current Six-Year Plan 1977-1983 are also being carried out in the Blue Nile and Kassala regions. Also, the recent shift in planning activities from comprehensive national road planning to comprehensive rural and feeder road

planning gives a good indication of the shift of emphasis from trunk roads building to feeder roads.* This evidence suggests that by the time the current main roads program is completed in the Blue Nile and Kassala regions, the government may decide that the rate of main road improvement should be gradually reduced and expenditure on the improvement and expansion of feeder roads be increased proportionately. If such a change of policy occurs, however, it will prejudice road development in other parts of the country, particularly those areas which have not yet been reached by modern road development to any significant degree (e.g., the three southern regions, Darfur, and Kordofan). More importantly, such a policy may result in road building activity whose outcome may violate the efficiency criteria upon which new improvements in the road system should be made. The change in policy may represent a misallocation of scarce capital that will affect the overall growth of the Sudanese economy. The concentration of modern main and feeder roads in the Kassala and Blue Nile regions, where developments are already well in progress, means that these regions will receive a disproportionately large share of total available resources and this will further increase their lead relative to the other regions. At the same time other less developed, but potentially rich regions in the southern and western parts of the country will receive only modest allocations of the road investment funds. In terms of economic efficiency criteria, this

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*Examples of rural and feeder roads planning are the Sudan Feeder Roads Master Plan Study of 1980 (118) and the Feasibility Study of Four Roads (108).

study has determined that investments should be made not only in the Blue Nile, Kassala, and Khartoum regions but also in the Kordofan, Darfur, and the Southern regions. The allocation of road investment funds in the model which has been determined on the basis of optimal decision criteria is shared among many regions. This distribution should ensure that a high level of service is maintained on the whole network.

Efficiency improvements within the existing road system should be the overriding goal of Sudanese road transportation policy, deviations from which require special justification on an individual project basis. The investment program suggested in this study has been determined by an efficiency-based model. In implementing the program, the country will be provided with the main infrastructure upon which other main or feeder roads could be later added for the purpose of stimulating agricultural and industrial production.

CHAPTER X

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

The primary objectives of this study have been to ascertain where within the Sudan road improvement would most increase network efficiency, what level of investment should be made to spur this road development, and to what standard various roads need to be upgraded in order to maximize overall interregional road network efficiency and, therefore, improve overall performance and quality of services offered by the roads. The study attempts to illuminate the features related to road transportation operation in the Sudan which have the most significant effect on its efficiency and development.

To accomplish the stated objectives an improvement planning model for road investment has been formulated and applied to the Sudanese interregional road network system. The model determines the investments which minimize total weighted ton-kilometers on the basis of relative travel time. In formulating the model careful consideration was given to conditions characteristic of the Sudan. Spatial variations in the distribution of existing and potential population and economic activities and the concomitant variation in level of traffic are elucidated. Different regions in the country are identified as areas of supply and/or demand and distances among those supply and demand regions are measured. A description of the pattern, structure, and characteristics of traffic flow over the existing road network system was conducted.

Variation in the growth of the road network from region to region revealed the extent of the effect of road network characteristics such as speed, travel time, road type and seasonality on level of road service. Road network development requirements may be ascribed to the existence of increasing demand for transport, spatially separated supply and demand points, and the low quality of service offered by the road transport facilities.

The investment programming model, which formed the investigative core of this research, was used to determine which roads should be improved, and to what standard they should be upgraded, given set levels of outlay needed to accomplish the improvements.

Tonnages of commodity traffic flows obtained for the year 1985 were used to calibrate the model. The flows represented an aggregation of various classes of commodities. A set of feasible interregional road links which represented specific spatial connections that existed in 1979 are defined in terms of link length and link type. Road standards are specified along with their associated upgrading costs. The standards were determined from actual Sudanese road construction experience; and the costs reflected prices for 1979. Weights associated with each road type were established on the basis of relative travel time. This measure reflects other aspects of Sudanese road network performance and quality of service such as risk of delay due to weather conditions. Since road improvements were sought for different given levels of budget invested, these capital outlays have been determined at levels which matched amount of funds allocated to road building in the country in the current Six-Year Plan 1977-1983.

The model formulated is a linearly-constrained nonlinear programming problem. It has the special property that if the route variables are fixed, the remaining optimization problem could be solved as a linear programming problem.

The heuristic procedure utilized to solve the model involved a cyclic operation in which a series of shortest path and modified optimization linear programming problems were alternatively solved at each level of investment sought. The cyclic heuristic employed a shortest path algorithm called TALLYHO and a program called Fixed Route Linear Programming (FRLP) which was used to prepare the problem for solution by a standard linear programming package (MPSX). TALLYHO was used to develop the shortest weighted routes on the basis of relative travel time, to determine link tonnages, and the value of the objective function as measured by total system ton-kilometers. The TALLYHO output, link tonnages, were fed into the FRLP in order to evaluate the various link loads generated by different road network link designs. The best combination of link improvements and standards which minimized total weighted ton-kilometers, and satisfied both capital invested and the fixed demand constraints could be, therefore, determined.

The model has been solved for seven budget levels, L$100, 125, 150, 175, 200, 225, and 250 million. To complete each solution and obtain final investments and the value of objective function entailed two or more cyclic operations of the heuristic in which the process of fixing routes and determining the investments was repeated. The final results were obtained when the routes in two successive runs of TALLYHO were the

same or the investments generated at two successive FRLP runs were the same. The results obtained in each solution included a set of investment projects. Each set has been differentiated by the road links which need to be improved, the link length (in kilometers) in need of upgrading, the standard to which the link should be upgraded, and the level of efficiency attained by the improved network associated with the set. This efficiency is derived after the value of the objective function has been evaluated. The evaluation is accomplished by comparing the weighted ton-kilometers over the original network to the weighted ton-kilometers over the improved network.

By allowing the budget level to vary, a tradeoff curve has been established between the value of the objective function (increase in efficiency) and capital invested. The results of this sensitivity analysis revealed that as the capital invested was increased beyond L$150 million, the marginal impact of each additional amount of money on network efficiency was less and less and the tradeoff of capital cost for efficiency gain approached equality. When the budget was increased from L$175 to 250 million, the substantial capital investment did not result in any appreciable impact on network efficiency. The comparison of these marginal returns to investment over all seven investment programs revealed that the benefits obtained with an investment of L$175 million exceeded those of alternative budgets and may, therefore, be the most desirable one when the financial constraints of a developing country like the Sudan are considered.

Also the analysis and comparison of results revealed that the set of projects developed in each of the first six solutions at lower

investment levels were part of a complementary set of investments generated in the final solution.

The model proved to be helpful in identifying investment priorities related to the improvement of interregional linkages in the country. From the analysis of patterns of investment generated by the model at different levels of capital invested, it has been found that the first priority of investment was accorded to links which connect the Khartoum and Blue Nile, Kassala and Blue Nile, and Khartoum and Kordofan regions. These were followed by improvements in links connecting the Kordofan and Darfur, Kordofan and Bahr El Ghazal, Blue Nile and Upper Nile, Upper Nile and Equatoria, and Khartoum and Northern regions. The pattern of investment generated resulted in a clear orientation of the improved network towards Khartoum and Port Sudan. The pattern of investment priorities and network configuration are responses to level of regional economic development and economic activities in the import-export sector, as well as the natural conditions. The improved network raised the network efficiency and increased the accessibility for the movement of cash crops.

Also a ranking of the road projects together with their associated costs was developed. The link tonnages generated by the model permitted the evaluation of the percentage contribution of individual upgraded links in improving overall network efficiency. This ranking of projects and identification of project costs may be helpful in phasing the program over the length of the planning period. Caution must be exercised, however, in using the static model developed here to plan

improvement sequences beyond a limited planning horizon. The model does not account for the interaction between road improvements and changes in interregional demand levels.

Current transportation policies in the Sudan may be characterized by undefined objectives and goals and changing procedures. If the recommended investment program developed in this study is implemented, it would be helpful in changing the current course of action in the Sudan.

An attempt was made to measure the degree to which the model results may deviate from optimality and to evaluate the general performance of the cyclic heuristic in generating the solutions of the model. This evaluation is made possible by reformulating the investment problem as an integer programming problem. The integer formulation is equivalent to the original nonlinear model but structurally different from it. Seven partial (fractional) linear programming solutions of the integer model were generated for the same given budget levels used in the original model. The objective function values obtained in these partial solutions were used as lower bounds in the optimal integer solutions and the heuristic solutions of the original model. When the previous solutions of the original model were evaluated with respect to the lower bounds, these solutions were found to deviate from full optimality by a range of only 2.9-7.5%. Evaluation of the cyclic heuristic method revealed that, in addition to its success in generating globally optimal or near optimal solutions, the procedure was highly efficient in generating these solutions as measured by CPU time and number of iterations needed for solution convergence.

Conclusions and Recommendations

The improved network configuration should serve and fully meet the demands placed on it in view of present knowledge about the development potential of the various regions of the Sudan. The program has been developed within the economic capability of the country to implement it and in compliance with national objectives. Furthermore, the model was formulated with consideration being given to operating conditions and characteristics of the road transportation system and the economy of the Sudan.

Although the heuristic method of solution does not guarantee a mathematically optimal solution, it has been shown to give good planning results for the conditions considered in the Sudan. These conditions are typical for many developing countries. This model is appropriate to use in the design of networks which improve efficiency in the Sudan, and should also be implementable in other developing countries given appropriate data specification. The fact that the total required computer time for the heuristic method is very small should make this planning model very attractive for practical application in those developing countries.

Specification of the number of kilometers of a link needed to be upgraded permitted calculation of total costs of individual projects obtained in the study. These cost figures can help determine total investment capital needed to make all necessary improvements in the system especially if the budget was not determined a priori. The link tonnages generated by the model have been used to establish ranking

priorities for the road projects obtained. Similarly, total ton-kilometers (the objective function value) can be useful in evaluating fleet requirements and making appropriate decisions about adjustment of fleet size required by the improved road system under study. Although the model has not been used to facilitate such decisions about fleet requirements in the present case, such an investigation would make a useful focus of a follow-up study. The value of objective function would reflect the optimal utility of the improved network system. If data on average mileage, capacity and load factors of the vehicles used were available, then these data would be used with the known total ton-kilometers of the system to derive the optimum number of vehicles needed to utilize the improved road system under study. If there is a shortage in number of vehicles, then the fleet could be upgraded, and if there is excess, it could be managed through appropriate government policies. In the Sudan, as in many other less developed countries, the government has much control of making decisions to expand or reduce vehicle fleet size; this is despite the fact that most of the vehicle fleet is privately owned.

This model, though simple in its structure and data requirements, has proved to be useful in generating an integrated plan in which investments, priority rankings, and perhaps fleet requirements can all be determined in one operation. This is an advantage to the use of this model that cannot be realized with other current road investment techniques. In determining investment priorities, the model does an adequate job of handling temporal patterns of investment over a short

planning horizon despite the fact that it is a single-period model. Examination of current literature indicate that there is no single-period road investment model developed thusfar which can be used to determine investments and their priorities over the planning period (4). To determine optimal priorities of link improvement, researchers usually resort to the use of dynamic programming [e.g, Barber (3), Ahmed (2), Bergendahl (9)] and/or heuristic numerical procedures which involve assigning weights to the projects [e.g., Adar (103), Lockheed (115)]. Dynamic programming is difficult to solve and often requires excessively high computation time (30). Results obtained on the basis of numerical procedures may be based on subjective evaluations and are, therefore, suspect. Such subjectivity has been noted in the case of Adar's study results (75).

Determining investment on the basis of accumulated ton load on links was found to be advantageous in identifying the most utilized road in the improved system. This improved road can be conceived of as the most strategically important road in the improved network system and would, therefore, be an investment priority.

The study demonstrated that partial improvements in links can be made and this can indeed decrease the value of the objective function despite the fact that only interregional movement was taken into account. The problem of adding partial improvements to links has been noted in other studies as one of the most serious theoretical deficiencies in models of road investment thusfar developed (43). The present model is, to my knowledge, the first one to handle the problem

of partial improvements effectively and allow specifically for improvement to be made in a continuous rather than discrete fashion. In doing this, the present model goes a step further in dealing with the complex problems of road investment planning.

By accommodating the problem of adding partial improvements to road links adequately in this study, one of the most bothersome problems in road transport planning has been overcome. One implication of the resolution of the partial improvement problem is that roads between and within regions can be connected and also serviced efficiently by an improved network. Nodes can be connected by partially improved links which would increase the value of the objective function. The value of the objective function in this case is a measure of level of service offered by an efficient network. Application of the model to improve an intra-urban transportation is limited without the addition of network capacity constraints. When applying the model in an urban context, the appropriate objective function would be to minimize weighted passenger-kilometers.

The optimum investments reflect the Sudanese economy because they are based on traffic demand that reflects the existing state of the regional and national economy and its development potential in 1985. That economy is characterized by strong tendency toward concentration in export-oriented economic activities and spatial concentration of these activities. This tendency will continue to exist, at least in the short-run period. In the long run drastic economic changes are likely to occur in the Blue Nile, Southern, and Northern regions. In the

Southern region, for example, there is an expanding economic activity associated with cash crops. Also the planned agro-based industries as well as other large development projects, such as the Jonglei Scheme, in the region will offer some new economic activities. A good part of the output will need to be shipped to the richer markets in the northern parts of the country and abroad through Port Sudan. Similar economic activities are also expected to prevail in the Northern region especially after the proposed modern Food System Program is carried out in the region. With all these new activities in the Southern and Northern regions, one can anticipate that high-valued commodities and perishables would provide a large share of the long-run future demand for transportation in those regions and may, therefore, stimulate the need, not only for new road improvements but also for high quality (paved) roads in those regions.

This road transportation model is not without limitations. Data problems account for most of the study's limitations. Most of the data utilized to execute the study were obtained from secondary sources. Problems were encountered in attempting to calibrate and apply the model. Notable here are the problems of determining costs of upgrading roads at different standards and at different locations and the inter-regional commodity traffic allocated to road transportation. The study did not consider passenger traffic. The effect of this omission on results is apparent in the case of the El Obied-Kosti link which has not been selected for improvement in any one of the solutions obtained for the model. The El Obied-Kosti link has relatively high traffic in the

movement of seasonal laborers from the Western region to the Blue Nile and Kassala regions. If passenger traffic were included in this analysis, then perhaps the investment results in connection to this particular link might have come out differently. Furthermore, the weights assigned to the different classes of roads, earth, gravel, pavement, were rather crude. It would be useful to develop more data concerning link performance such as speed, travel time, costs, congestion, and risk of delay due to weather, and use them in a formal procedure to improve the quality of these weights. Such a procedure can be developed, for example, on the basis of an ordinal weighting approach in which differences in the relative importance of various link performance measures could be accounted for.

Costs of upgrading roads at different standards vary depending on topography; these differential costs were not accounted for in the model. These differential costs could easily be incorporated in the model if such data were available. The model structure can be varied to accommodate this problem of differential costs assuming such data are available. It would, for example, be possible to accurately derive total upgrading costs of individual road projects by using different per-kilometer costs and, therefore, determine total amount of investment capital which would be needed to execute the road projects. Estimated per-kilometer cost for each level of road improvement might incorporate various cost components which reflect regional variation in topography, terrain, soil, labor cost, availability of material for construction, taxes, and land acquisition costs. One could develop a multiobjective

function in the model which minimizes total weighted ton-kilometers on earthen roads, total weighted ton-kilometers on gravel, and total ton-kilometers on paved roads, rather than one objective function which minimizes the sum of all these variables.

The model did not consider construction of new roads. New construction could be incorporated in the model in the form of building a link from nothing to earth, nothing to gravel, and nothing to pavement. These variables would be incorporated in the objective function framework.* Also, the objective function could be modified to minimize cost instead of weighted ton-kilometers. Without incorporating conjestion costs, the physical measure (i.e., reduction of weighted ton-kilometers) is linearly related to cost anyway. It would be easy to replace weights with cost per ton-kilometer coefficients for each road type. This figure could include only operating and maintenance cost, or it could include amortized investment cost as well. If such costs are to be used as the only optimization criteria in the model, however, they should be viewed with much caution because of the quality of cost data available in most developing countries.

Another limitation of the study concerns the problem of aggregating all commodities into one class. Data on commodity flows (i.e., demand) used in virtually all road investment models are, more or less,

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*In this case of adding new links, the new link constraint would have a different property. A new link investment has no contribution (i.e., cannot be used) until the entire link design to earth, gravel, or pavement standard is finished.

aggregated for analytical purposes. For instance, in most application-oriented multicommodity road investment models [e.g., Ahmed (2)], aggregation is necessary in order to manage the size of formulation that can be solved. In formulating such models it might, therefore, be practically impossible to incorporate a large number of commodities and then solve the model. A multicommodity road investment model which uses a few selected major commodities, in a disaggregated fashion, would actually be using data which are only approximate measures of traffic volume in a region or country under study; whereas a model which is capable of handling an unlimited multitude of commodities, albeit in an aggregate fashion such as the present model, might be using data which are relatively more precise measures of traffic volume. It is the total volume of traffic which determines road transportation investments. Road investments are affected by the absolute total volume of traffic rather than by the number or type of commodities considered in the analysis.

Another limitation to be noted is related to scope of the problem solved. The size of the Sudanese network analyzed is relatively small, composed of only 10 nodes and 15 links. Yet, in spite of the apparently simple structure of the network, the problem addressed represents almost the same combinatorial difficulties as those of all large network investment problems. In any more complicated model form (e.g., the equivalent integer formulation shown in Chapter VIII of this dissertation) the network evaluation would take much more time and money.

Finally, the model is a static one in that investments were undertaken which maximized the improvements over a short period of time while satisfying a fixed demand. The model can, however, accommodate changes of demand flows if data can be made available on a long-term forecast basis; and, therefore, the model could be modified to handle intertemporal patterns of investment. A characteristic of the model which needs further study is, therefore, the variability of solutions with the length of the planning period and the selection and time phasing of investment over a long period or number of periods. When the model is extended to treat intertemporal investments in a framework of variable supplies and demands, it can accommodate the interdependencies between these supplies and demands of traffic and improved network efficiency, for it is clear that increasing efficiency through link improvements will result in changes in supply and demand patterns.

In considering intertemporal investments (i.e., scheduling of investments over one period or number of periods) two approaches may prove to be fruitful: dynamic and myopic (32). The former approach seeks to sequence investments such that the objective function is minimized or maximized over the entire planning process (allowing the implicit consideration of all sequences), whereas the latter minimizes or maximizes the objective function over each stage or period. The present model has already been shown to be capable of handling temporal patterns of investments over a single planning period. There seems to be no reason why such a model, using different planning periods when reapplied periodically (as a myopic model) cannot be just as useful as a

dynamic model.* In modifying the present model and using it to determine intertemporal investments, it would be interesting to use both dynamic and myopic approaches and then compare the results to see whether or not the sequences of link improvements coincide for both sets of programs generated by the two methods.

From the foregoing discussion it is apparent that most of these limitations can be overcome or are not serious ones. With more refined and complete data, the model could be made more realistic, but probably at the expense of increased complexity of numerical solution.

Despite the limitations imposed by the data and other shortcomings of the study, this research has accomplished its objectives and provided an investment program and planning process which, it is hoped, will lay the basis for future development of an efficient road transportation system in the Sudan. In the context of large scale road transportation investment in the Sudan, the planning method represents a logical and effective alternative to the political approach so much in evidence in the country. By attempting to tailor improvements in the road network and its efficient performance to evolving traffic needs substantial savings in road investment might accrue. As the data base is expanded and improved in quality, the model can be reapplied and better knowledge of the interrelationships between transportation and the rest of the

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*Hodgson (32) evaluated the two approaches (dynamic and myopic) in a context of two empirical examples of a road investment scheduling problem and he found almost no advantage in employing dynamic programming technique over myopic to determine optimal sequence of road network improvements.

economy in the Sudan can be gained. The practical use of the model for evaluation of road development projects provide great promise for the Sudan.

REFERENCES

REFERENCES

1. Abdulaal, M., and Leblank, L., "Continuous Equilibrium Network Design Models," in Boyce, D. (ed.), "Transportation Network Designs," a special issue of the Journal of Transportation Research, 13B, No. 1, 1979.

2. Ahmed, Y., and O'Sullivan, P., and others, Road Investment Programming for Developing Countries: An Indonesian Example. The Transportation Center at Northwestern University, Evanston, Illinois, 1976.

3. Barber, G. M., "A Mathematical Programming Approach to a Network Development Problem," Economic Geography, 51, 1975.

4. _____, "Sequencing Highway Network Improvements: A Case Study of South Sulawesi," Economic Geography, 53, 1977.

5. _____, and Ralston, B. A., "The Elementary Dynamics of Road Development," Geographic Analysis, 12, No. 3, 1980.

6. _____, "Dynamic Road Investment Policy: A Recursive Version of the Ellet-Walters Model," unpublished research paper, Department of Geography, The University of Tennessee, Knoxville, 1980.

7. _____, "The Dynamics of Transportation Development," unpublished research paper, Department of Geography, The University of Tennessee, Knoxville, 1980.

8. Bergendahl, G., "Capacity Planning Models for Systems of Plant and Road Investments," Swedish Journal of Economics, 7, 1968.

9. _____, "A Combined Linear and Dynamic Programming Model for Interdependent Road Investment Planning," Transportation Research, 3, 1969.

10. Billheimer, J. W., and Gray, P., "Network Design with Fixed and Variable Cost Elements," Transportation Science, 7, 1973.

11. Boyce, D. E., "Introduction," in Boyce, D. (ed.), "Transportation Network Designs," a special issue of the Journal of Transportation Research, 13B, No. 1, 1979.

12. _____, and others, "Optimal Network Problem: A Branch and Bound Algorithm," Environment and Planning, 5, 1973.

13. Branston, D., "Link Capacity Functions: A Review," Transportation Research, 10, 1976.

14. Bronzini, M. S., and others, "A Transportation Sensitive Model of a Regional Economy," Transportation Research, 8, 1974.

15. Campbell, T. C., "Transportation in Developing Countries: Special Reference to Kenya," Traffic Quarterly, 28, 1974.

16. Carroll, J., "Some Aspects of the Future Development of Transport in Tropical Africa," in Smerk, G. M. (ed.), Essays on Transportation Problems in the 1970's. Graduate School of Business, Indiana University, Bloomington, 1969.

17. Carter, E. C., and Stowers, J. R., "Models for Fund Allocation for Urban Highway System Capacity Improvements," Highway Research Record, 70, 1963.

18. Chan, Y. P., "Optimal Travel Time Reduction in a Transport Network: An Application of Network Aggregation and Branch and Bound Techniques," Research Report R69-39, MIT, Department of Civil Engineering, Cambridge, Massachusetts, 1969.

19. _____, "The Transportation Network Investment Problem: A Survey of Tree-Search Solution Algorithms," Technical Note 105, The Penn. Transportation Institute, The Penn. State University, University Park, Pennsylvania, 1976.

20. Chapman, L. D., "Investing in Regional Highway Networks," Transportation Engineering Journal, TE2, 1973.

21. Church, R. L., and Bell, T. L., "Developing a Heuristic Approach to Power Plant Siting Models," Chapter 4 in Power Plant Siting Heuristics, Optimization and Alternative Configuration Generation." Report for the Department of Energy, Office of the Assistant Secretary for the Environment, 1981 (forthcoming).

22. Cole, L. M., "Transport Investment Strategies and Economic Development," Land Economics, 44, 1968.

23. Danzig, G. B., and others, "Formulating and Solving the Network Design Problem by Decomposition," in Boyce, D. (ed.), "Transportation Network Designs," a special issue of the Journal of Transportation Research, 13B, No. 1, 1979.

24. Due, J. F., "The Problems of Rail Transportation in Tropical Africa," The Journal of Developing Areas, 13, 1972.

25. Frey, S., and Nemhauser, G., "Temporal Expansion of a Transportation Network--I and II," Transportation Science, 6, 1972.

26. Fulkerson, D., "Increasing the Capacity of a Network: A Parametric Budget Problem," Management Science, 5, 1959.

27. Garrison, W. L., and Marble, D. F., "Analysis of Highway Networks: A Linear Programming Formulation," Highway Research Board, 37, 1958.

28. Goldman, A. J., and Nemhauser, G. L., "A Transport Improvement Problem," Transportation Science, 1, 1967.

29. Hammer, P. L., "Increasing the Capacity of a Network," Canadian Operations Research Society Journal, 7, 1969.

30. Hay, G., and others, "Toward Optimal Planning of a Two-Mode Urban Transportation System: A Linear Programming Formulation," Highway Research Record, 148, 1966.

31. Heiner, M. M., "Heuristic Procedures for Solving Combinitorial Optimization Problems in Transportation," Transportation Research, 8, 1976.

32. Hodgson, M., "Staging Interurban Highway Construction by Dynamic Programming," Annals of Regional Science, 8, 1973.

33. Hurst, M. E. (ed.), Transportation Geography: Comment and Readings, McGraw-Hill Series in Geography, New York, 1974.

34. Hutchinson, B. G., "Programming of Regional Highway Investments," Transportation Engineering Journal, TE3, 1972.

35. Kalaba, R., and Juncosa, M., "Optimum Design and Utilization of Communication Networks," Management Science, 3, 1956.

36. Kresge, D. T., and Roberts, P. O., "Systems Analysis and Simulation Models," Technique of Transport Planning, Vol. 1, (Meyer, J. R., ed.), Brookings Institute, Washington, 1971.

37. Kuhn, T. E., and Lea, N. D., "Engineering-Economic Systems and Analysis for Transport Planning in Dahomey, West Africa," Highway Research Record, 285, 1969.

38. Leaman, J. H., and Conkling, E. C., "Transport Change and Agricultural Specialization," Annals of the Association of American Geographers, 65, 1975.

39. Leblanc, L. J., "An Algorithm for the Discrete Network Design Problem," Transportation Science, 9, 1975.

40. _____, "Global Solutions for a Nonconvex Concave Rail Network Model," Management Science, 23, 1976.

41. MacKinnon, R. D., "Dynamic Programming and Geographical Systems," Economic Geography, XLVI (supplement), 1970.

42. _____, and Barber, G. M., "Optimization Models of Transportation Network Improvement: Review and Future Prospects," Proceedings, Conference on Optimization Methods Applied to Transportation Systems, International Institute for Applied Systems Analysis, Vienna, 1976.

43. _____, and Hodgson, M. J., "Optimal Transportation Networks: A Case Study of Highway Systems," Environments and Planning, 2, 1970.

44. Morlok, E. K., An Analysis of Transport Technology and Network Structure, The Transportation Center, Northwestern University, Evanston, Illinois.

45. _____, "A Goal-Directed Transportation Planning Model," Transportation Research, 4, 1970.

46. _____, and others, A Multiple-Mode Transportation Network Design Model, The Transportation Center, Northwestern University, Evanston, Illinois, 1969.

47. O'Sullivan, P., "Regional Road Investment Planning for Developing Countries: An Indonesian Application," Chapter 16 in Physical and Human Geography, Bristol Essays (Ronald, P., Chisholm, and Hagget, P., eds.), London, 1975.

48. Quandt, R. E., "Models of Transportation and Optimal Network Construction," Journal of Regional Science, 2, 1960.

49. Ridley, T. M., "An Investment Policy to Reduce the Travel Time in a Transportation Network," Transportation Research, 2, 1968.

50. Roberts, P. O., "Selecting and Staging Additions to a Transport Network," in Meyer, J. R., ed., Techniques of Transport Planning, vol. 1, The Brookings Institute, Washington, 1971.

51. Hofmeier, Rolf, Transport and Economic Development in Tanzania, Weltforum Verla, Munchen, Germany, 1973.

52. Scott, A. J., "A Programming Model of an Integrated Transportation Network," Papers, Regional Science Association, 19, 1967.

53. _____, "The Optimal Network Problem: Some Computational Procedures," Transportation Research, 3, 1969.

54. _____, "An Introduction to Spatial Allocation Analysis," Association of American Geographers, Resource Paper, No. 9, 1971.

55. Stairs, S., "Selecting an Optimal Traffic Network," Journal of Transport Economics and Policy, 1968.

56. Steenbrink, P. A., "Transport Network Optimization in the Dutch Integral Transportation Study," Transportation Research, 8, 1974.

57. _____, Optimization of Transport Networks, Wiley, New York, 1974.

58. Tomlin, J. A., "Minimum-Cost Multicommodity Network Flows," Operations Research, 14, 1966.

59. United Nations Environment Programme, "Desertification Control," The Semi-Annual Bulletin on Plans and Activities, vol. 1, no. 2, 1978.

60. Wang, J., and others, "Toward a Solution for the Optimal Allocation of Investments in Urban Transportation Networks," Highway Research Record, 238, 1968.

61. Wilson, G. W., "Case Studies of Effect of Roads on Development," Highway Research Record, 15, 1966.

62. _____, and others, The Impact of Highway Investment on Development, The Brookings Institute, Washington, 1966.

63. Zangwill, W., Nonlinear Programming: Unified Approach, Prentice-Hall, Englewood Cliffs, New Jersey, 1969.

64. Aramco, "Farming in the Arab East," Aramco World Magazine, 1978.

65. Al-Masayer, M. Z., Sudan Economy in Twenty Years: 1956-1975, Cairo, 1972.

66. Barbour, K. M., The Republic of the Sudan: A Regional Geography, University of London Press, 1961.

67. Betz, M. J., III, "An Analysis of Transportation Costs in the Sudan and an Approach to the Engineering Analysis for Transportation Planning in Developing Countries," unpublished Ph.D. dissertation, Northwestern University, Evanston, Illinois, 1961.

68. Gunther, H., "Social Geographic Problems in the Khasm El Ghirba Project, Sudan," Land Reform, Food and Agriculture Organization of the United Nations, No. 2, Rome, 1978.

69. Gusten, R., Problems of Economic Growth and Planning: The Sudan Example, translated copy by R. C. Freeston, Berlin, Germany, 1966.

70. Heinz-Ulrich, Thimm, Development Projects in the Sudan: An Analysis of Their Reports with Implications for Research and Training in Arid Land Management, The United Nations University, Tokyo, Japan, 1979.

71. Hill, R., Sudan Transport, Oxford University Press, London, 1965.

72. Imam, F. B. (ed.), Improvement of Transportation to Service Development in the Sudan (in Arabic), Institute for Extra-Mural Studies, University of Khartoum, Sudan, 1968.

73. International Labor Office, Growth, Employment, and Equity: A Comprehensive Strategy for the Sudan, Geneva, 1975.

74. Lebon, J. H. G., "Desert Motor Routes in Northern Sudan," Geography, 39-40, 1955.

75. Lees, F., and Brooks, H., The Economic and Political Development of the Sudan, The Macmillan Press, London, 1977.

76. Mabbutt, J. A. (ed.), Proceedings of the Khartoum Workshop on Arid Lands Management, The University of Khartoum, The United Nations University, Tokyo, Japan, 1979.

77. Martin, E. A., "The Gezira Scheme: An Illusion of Development, A Review Article," Economic Development and Cultural Change, vol. 28, no. 3, 1980.

78. Nelson, H. D., and others, Area Hand-Book for the Democratic Republic of the Sudan, Washington, 1973.

79. Saaty, T. L., "Scenarios and Priorities in Transport Planning: Application to the Sudan," Transportation Research, 11, 1977.

80. Shankar, N. A., Incentives for Resource Allocation: A Case Study of Sudan, World Bank Staff Working Paper No. 367, Washington, 1979.

81. Sudan Today, University Press of Africa, Nairobi, Kenya, 1971.

82. Wilkins, C., "Transport in the Sudan," Chapter 5 in El-Hassan, A. M. (ed.), An Introduction to Sudan Economy, Khartoum University Press, Sudan, 1976.

83. Wynn, R. F., "The Sudan's 10-Year Plan of Economic Development, 1961/62-1970/71: An Analysis of Achievement to 1967-1968," The Journal of Developing Areas, 5, 1971.

84. Sudan Department of Statistics, Internal Trade Statistics, 7 vols., Khartoum, Sudan, 1970-1976.

85. _____, Statistical Book, Khartoum, Sudan, 1973.

86. _____, Industrial Survey, 1972/1973, Khartoum, Sudan, 1976.

87. Sudan Tourism and Hotels Corporation, A Tourist Guide to Sudan: Basic Facts and Figure, Khartoum, Sudan, n.d.

88. Sudan Ministry of Agriculture, Food and Natural Resources, Sudan Yearbook of Agricultural Statistics, (and supplement for 1979), Khartoum, Sudan, 1977.

89. Sudan Ministry of Culture and Information, Sudan Facts and Figures, Report, Khartoum, Sudan, 1974.

90. Sudan Ministry of Finance and National Economy, Economic Survey Bulletins, Khartoum, Sudan, 1971-1979.

91. Sudan Ministry of National Planning, Freight Traffic Estimation Study, Khartoum, Sudan, 1978.

92. _____, Growth of Transport Facilities in the Sudan, Khartoum, Sudan, 1978.

93. _____, Sugar Transport Study, Khartoum, Sudan, 1978.

94. _____, Road Traffic Densities on the Major Roads in the Sudan, Khartoum, Sudan, 1978.

95. _____, Truck Operating Characteristics in the Sudan, Khartoum, Sudan, 1978.

96. _____, Transport Statistical Bulletin, 4 vols., Khartoum, Sudan, 1974-1977.

97. _____, Six-Year Plan: Transport and Communications Sector 1977-1983, Khartoum, Sudan, 1978.

98. _____, Road Toll Financing Feasibility Study, Khartoum, Sudan, 1978.

99. _____, The Six-Year Plan of Economic and Social Development 1977/78-1982/83, vols. I and II, Khartoum, Sudan, 1977.

100. _____, Origin and Destination Statistics: Road Traffic Survey, 1975.

101. _____, and Sudan Railway Corporation, Wagon Stock Utilization Study, Khartoum, Sudan, 1978.

102. _____, and Tenneco, Inc., A Comprehensive Plan for a Food System in the Sudan, unpublished proposal, Khartoum, Sudan, 1977.

103. Adar (Association for the Development of Arab Resources), The Sudan Transport Study, 5 vols., Khartoum, Sudan, 1975.

104. Bceom, Inc., Highway Feasibility Study, inception report, Khartoum, Sudan, 1975.

105. _____, Highway Feasibility Study: Summary and Recommendations, final report, Khartoum, Sudan, 1976.

106. _____, Highway Feasibility Study (El Obied-Dubeibat Road), final report, Khartoum, Sudan, 1976.

107. Campbell, J. R., Sudan Roads, United Nations Technical Assistance Report, Khartoum, Sudan, 1957.

108. Dorsch Consult, and Gitec Consult, Feasibility Study of Four Roads (Gedaref-Um Barakit, Wad El-Huri-SimSim, Suki-Gedaref, Rabak-Renk), Khartoum, Sudan, 1977.

109. Economic Commission for Africa, Summaries of Economic Data for Sudan, 6th year, no. 37, United Nations, New York, 1975.

110. International Marketing Bureau, Marketing in the Sudan, Overseas Business Reports, Washington, 1977.

111. Japan International Agency, Feasibility and Preliminary Engineering Study of Road Project (El-Obied-Um Ruwaba, Khartoum, Sudan, 1978.

112. Kamil Mansour, Crops Production in Relation to Environment in the Sudan, unpublished discussion paper, n.d.

113. Keymer, R. C., Roads and Road Transport, discussion paper, The Sudan Road Association, Khartoum, Sudan, 1953.

114. Kocks KG, Consulting Engineers, Rehabilitation of the Juba-Wau Road (Lainya-Tambura Section), Khartoum, Sudan, 1975.

115. Lockheed, Inc., Transportation Development Planning: Sudan, 2 vols., pt. 1, 2, 1968.

116. Louis Berger, Inc., Report of Highway Design, Construction, and Financing, Khartoum, Sudan, 1973.

117. Mustafa Khogali, Importance of Transportation for Regional Specialization in the Sudan (in Arabic), n.d.

118. Norconsult, A. S., Sudan Feeder Roads Master Plan (draft final report, 2 vols., pt. A-D, Khartoum, Sudan, 1980.

119. _____, Sudan Feeder Roads Master Plan (inception report), Khartoum, Sudan, 1979.

120. _____, Kenya-Sudan Road Link, final report, Khartoum, Sudan, 1978.

121. _____, Feasibility and Preliminary Engineering Study (Kosti-Umm Ruwaba Road) (final report), text volume, Khartoum, Sudan, 1978.

122. Samir El-Khouri, "Sudan Carries Out Broad Program of Reform, But Faces Further Problems in Medium Term," IMF Survey Report, vol. 9, no. 17, 19780.

123. "Reach for the Future: A Review of Sudan," The Economist, 1978.

124. World Bank, "IDA Provides $40 Million Credit to Sudan for New Halfa Irrigation Scheme Rehabilitation," IDA News Release, no. 80/72, May 19, 1980.

125. _____, "IDA Provides $65 Million for Sudan Agriculture Rehabilitation Program," IDA News Release, no. 80/35, April 10, 1980.

126. _____, "IDA to Provide $65 Million for Power Project in Sudan," IDA News Release, no. 80/42, April 21, 1980.

APPENDIXES

APPENDIX A

RESULTS OF TALLYHO AND FRLP OBTAINED IN SOLUTION #1 (BUDGET = 100)

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CSENTRY
ROUTE FROM   1   2
ROUTE FROM   1   2   3
ROUTE FROM   1   2   4
ROUTE FROM   1   2   5
ROUTE FROM   1   2   5   6
ROUTE FROM   1   2   4   7
ROUTE FROM   1   2   5   8
ROUTE FROM   1   2   4   7   9
ROUTE FROM   1  10
ROUTE FROM   2   3
ROUTE FROM   2   4
ROUTE FROM   2   5
ROUTE FROM   2   5   6
ROUTE FROM   2   4   7
ROUTE FROM   2   5   8
ROUTE FROM   2   4   7   9
ROUTE FROM   2   3  10
ROUTE FROM   3   4
ROUTE FROM   3   2   5
ROUTE FROM   3   2   5   6
ROUTE FROM   3   4   7
ROUTE FROM   3   2   5   8
ROUTE FROM   3   4   7   9
ROUTE FROM   3  10
ROUTE FROM   4   5
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ROUTE FROM   4   7   9
ROUTE FROM   4   3  10
ROUTE FROM   5   6
ROUTE FROM   5   7
ROUTE FROM   5   8
ROUTE FROM   5   8   9
ROUTE FROM   5   2   3  10
ROUTE FROM   6   5   7
ROUTE FROM   6   8
ROUTE FROM   6   8   9
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ROUTE FROM   6   5   2   3  10
ROUTE FROM   7   5   8
ROUTE FROM   7   9
ROUTE FROM   7   4   3  10
ROUTE FROM   8   9
ROUTE FROM   8   5   2   3  10
ROUTE FROM   9   7   4   3  10
```

			b	c
1	1	2	44.98	38322.89
2	1	10	14.70	17978.10
3	3	10	396.36	220375.20
4	2	3	141.01	89823.31
5	3	4	214.38	228100.20
6	2	4	85.90	44582.09
7	2	5	187.14	218766.50
8	4	5	15.60	15116.40
9	4	7	66.92	63239.35
10	5	7	7.64	10069.52
11	5	8	54.96	87221.38
12	5	6	56.76	125666.40
13	6	8	4.88	14342.32
14	8	9	4.03	6448.00
15	7	9	45.51	126426.60
TOTAL	TON/KM=		1496476.53	

```
140.                                  a
TO NODE     852.0
TO NODE    1489.0
TO NODE    1371.0
TO NODE    2021.0
TO NODE    4235.0
TO NODE    2316.0
TO NODE    3608.0
TO NODE    5094.0
TO NODE    1223.0
TO NODE     637.0
TO NODE     519.0
TO NODE    1169.0
TO NODE    3383.0
TO NODE    1464.0
TO NODE    2756.0
TO NODE    4242.0
TO NODE    1193.0
TO NODE    1064.0
TO NODE    1806.0
TO NODE    4020.0
TO NODE    2009.0
TO NODE    3393.0
TO NODE    4787.0
TO NODE     556.0
TO NODE     969.0
TO NODE    3183.0
TO NODE     945.0
TO NODE    2556.0
TO NODE    3723.0
TO NODE    1620.0
TO NODE    2214.0
TO NODE    1318.0
TO NODE    1587.0
TO NODE    3187.0
TO NODE    2362.0
TO NODE    3532.0
TO NODE    2939.0
TO NODE    4539.0
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TO NODE    4576.0
TO NODE    2905.0
TO NODE    2778.0
TO NODE    2565.0
TO NODE    1600.0
TO NODE    3949.0
TO NODE    5343.0
```

[a]Route weighted distance

[b]Link tonnage

[c]Weighted ton-kilometers

..MPSX-V1M7.. FIXED ROUTE LINEAR PROGRAMMING INVESTMENT PROBLEM

SECTION 2 - COLUMNS

NUMBER	.COLUMN.	AT	...ACTIVITY...	..INPUT COST..	..LOWER LIMIT.	..UPPER LIMIT.	.REDUCED COST.
19	EG10102	LL	.	44.98000-	.	NONE	11.78000
20	EP10102	LL	.	89.96000-	.	NONE	25.92500
21	EG10110	LL	.	14.70000-	.	NONE	42.06000
22	EP10110	LL	.	29.40000-	.	NONE	86.48500
23	EG10304	LL	.	214.38000-	.	NONE	155.25500
24	EP10304	BS	246.00000	428.76000-	.	NONE	.
25	EG10205	LL	.	210.38000-	.	NONE	151.25500
26	EP10205	BS	378.00000	420.76000-	.	NONE	.
27	EG10405	LL	.	.	.	NONE	56.76000
28	EP10405	LL	.	.	.	NONE	115.88500
29	EG10407	LL	.	74.56000-	.	NONE	15.43500
30	EP10407	BS	315.00000	149.12000-	.	NONE	.
31	EG10507	LL	.	.	.	NONE	56.76000
32	EP10507	LL	.	.	.	NONE	115.88500
33	EG10508	LL	.	54.96000-	.	NONE	1.80000
34	EP10508	LL	.	109.92000-	.	NONE	5.96500
35	EG10506	BS	39.60417	56.76000-	.	NONE	.
36	EP10506	LL	.	113.52000-	.	NONE	2.36500
37	EG10608	LL	.	4.88000-	.	NONE	51.88000
38	EP10608	LL	.	9.76000-	.	NONE	106.12500
39	EG10709	LL	.	45.51000-	.	NONE	11.25000
40	EP10709	LL	.	91.02000-	.	NONE	24.86500
41	GP10204	BS	103.00000	109.14000-	.	NONE	.
42	GP10508	LL	.	54.96000-	.	NONE	14.80750
43	GP10608	LL	.	4.88000-	.	NONE	64.88750
44	GP10809	LL	.	4.03000-	.	NONE	65.73750
45	GP10709	LL	.	45.51000-	.	NONE	24.25750

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                ENTRY
 ROUTE FROM   1   2
 ROUTE FROM   1   2   3
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 ROUTE FROM   5   2   3  10
 ROUTE FROM   6   5   2   4   7
 ROUTE FROM   6   8
 ROUTE FROM   6   8   9

 ROUTE FROM   6   5   2   3  10
 ROUTE FROM   7   4   2   5   8
 ROUTE FROM   7   9
 ROUTE FROM   7   4   3  10
 ROUTE FROM   8   9
 ROUTE FROM   8   5   2   3  10
 ROUTE FROM   9   7   4   3  10
    1    1    2      44.98      38322.89
    2    1   10      14.70      17978.10
    3    3   10     396.36     220375.20
    4    2    3     141.01      89823.31
    5    3    4     214.38     122625.30
    6    2    4     109.14      45402.22
    7    2    5     210.38      86886.81
    8    4    5       0.00          0.00
    9    4    7      74.56      23486.38
   10    5    7       0.00          0.00
   11    5    8      54.96      67221.38
   12    5    6      56.76     123418.70
   13    6    8       4.88      14342.32
   14    8    9       4.03       6448.00
   15    7    9      45.51     126426.60
TOTAL TON/KM=     1002757.00
```

```
140.
        TO NODE      852.0
        TO NODE     1489.0
        TO NODE     1268.0
        TO NODE     1265.0
        TO NODE     3439.4
        TO NODE     1583.0
        TO NODE     2852.0
        TO NODE     4361.0
        TO NODE     1223.0
        TO NODE      637.0
        TO NODE      416.0
        TO NODE      413.0
        TO NODE     2587.4
        TO NODE      731.0
        TO NODE     2000.0
        TO NODE     3509.0
        TO NODE     1193.0
        TO NODE      572.0
        TO NODE     1050.0
        TO NODE     3224.4
        TO NODE      887.0
        TO NODE     2637.0
        TO NODE     3665.0
        TO NODE      556.0
        TO NODE      829.0
        TO NODE     3003.4
        TO NODE      315.0
        TO NODE     2416.0
        TO NODE     3093.0
        TO NODE     1128.0
        TO NODE     2174.4
        TO NODE     1144.0
        TO NODE     1587.0
        TO NODE     3187.0
        TO NODE     1606.0
        TO NODE     3318.4
        TO NODE     2939.0
        TO NODE     4539.0

        TO NODE     3780.4
        TO NODE     2731.0
        TO NODE     2778.0
        TO NODE     1443.0
        TO NODE     1600.0
        TO NODE     3193.0
        TO NODE     4221.0
```

[a] Route weighted distance

[b] Link tonnage

[c] Weighted ton-kilometers

..MPSX-V1M7.. FIXED ROUTE LINEAR PROGRAMMING INVESTMENT PROBLEM

SECTION 2 - COLUMNS

NUMBER	.COLUMN.	AT	...ACTIVITY...	..INPUT COST..	..LOWER LIMIT.	..UPPER LIMIT.	.REDUCED COST.
19	EG10102	LL	.	44.98000-	.	NONE	11.78000
20	EP10102	LL	.	89.96000-	.	NONE	25.92500
21	EG10110	LL	.	14.70000-	.	NONE	42.06000
22	EP10110	LL	.	29.40000-	.	NONE	86.48500
23	EG10304	LL	.	214.38000-	.	NONE	155.25500
24	EP10304	BS	246.00000	428.76000-	.	NONE	.
25	EG10205	LL	.	210.38000-	.	NONE	151.25500
26	EP10205	BS	378.00000	420.76000-	.	NONE	.
27	EG10405	LL	.	.	.	NONE	56.76000
28	EP10405	LL	.	.	.	NONE	115.88500
29	EG10407	LL	.	74.56000-	.	NONE	15.43500
30	EP10407	BS	315.00000	149.12000-	.	NONE	.
31	EG10507	LL	.	.	.	NONE	56.76000
32	EP10507	LL	.	.	.	NONE	115.88500
33	EG10508	LL	.	54.96000-	.	NONE	1.80000
34	EP10508	LL	.	109.92000-	.	NONE	5.96500
35	EG10506	BS	39.60417	56.76000-	.	NONE	.
36	EP10506	LL	.	113.52000-	.	NONE	2.36500
37	EG10608	LL	.	4.88000-	.	NONE	51.88000
38	EP10608	LL	.	9.76000-	.	NONE	106.12500
39	EG10709	LL	.	45.51000-	.	NONE	11.25000
40	EP10709	LL	.	91.02000-	.	NONE	24.86500
41	GP10204	BS	103.00000	109.14000-	.	NONE	.
42	GP10508	LL	.	54.96000-	.	NONE	14.80750
43	GP10608	LL	.	4.88000-	.	NONE	64.88750
44	GP10809	LL	.	4.03000-	.	NONE	65.73750
45	GP10709	LL	.	45.51000-	.	NONE	24.25750

APPENDIX B

FINAL RESULTS OF TALLYHO AND FRLP OBTAINED IN SOLUTION #2 (BUDGET = 125)

CSENTRY 140.

Route						To	Distance
ROUTE FROM	1	2				TO NODE	852.0[a]
ROUTE FROM	1	2	3			TO NODE	1489.0
ROUTE FROM	1	2	4			TO NODE	1268.0
ROUTE FROM	1	2	5			TO NODE	1265.0
ROUTE FROM	1	2	5	6		TO NODE	2918.6
ROUTE FROM	1	2	4	7		TO NODE	1583.0
ROUTE FROM	1	2	5	8		TO NODE	2852.0
ROUTE FROM	1	2	4	7	9	TO NODE	4361.0
ROUTE FROM	1	10				TO NODE	1223.0
ROUTE FROM	2	3				TO NODE	637.0
ROUTE FROM	2	4				TO NODE	416.0
ROUTE FROM	2	5				TO NODE	413.0
ROUTE FROM	2	5	6			TO NODE	2066.6
ROUTE FROM	2	4	7			TO NODE	731.0
ROUTE FROM	2	5	8			TO NODE	2000.0
ROUTE FROM	2	4	7	9		TO NODE	3509.0
ROUTE FROM	2	3	10			TO NODE	1193.0
ROUTE FROM	3	4				TO NODE	572.0
ROUTE FROM	3	2	5			TO NODE	1050.0
ROUTE FROM	3	2	5	6		TO NODE	2703.6
ROUTE FROM	3	4	7			TO NODE	887.0
ROUTE FROM	3	2	5	8		TO NODE	2637.0
ROUTE FROM	3	4	7	9		TO NODE	3665.0
ROUTE FROM	3	10				TO NODE	556.0
ROUTE FROM	4	2	5			TO NODE	829.0
ROUTE FROM	4	2	5	6		TO NODE	2482.6
ROUTE FROM	4	7				TO NODE	315.0
ROUTE FROM	4	2	5	8		TO NODE	2416.0
ROUTE FROM	4	7	9			TO NODE	3093.0
ROUTE FROM	4	3	10			TO NODE	1128.0
ROUTE FROM	5	6				TO NODE	1653.6
ROUTE FROM	5	2	4	7		TO NODE	1144.0
ROUTE FROM	5	8				TO NODE	1587.0
ROUTE FROM	5	8	9			TO NODE	3187.0
ROUTE FROM	5	2	3	10		TO NODE	1606.0
ROUTE FROM	6	5	2	4	7	TO NODE	2797.6
ROUTE FROM	6	8				TO NODE	2939.0
ROUTE FROM	6	8	9			TO NODE	4539.0
ROUTE FROM	6	5	2	3	10	TO NODE	3259.6
ROUTE FROM	7	4	2	5	8	TO NODE	2731.0
ROUTE FROM	7	9				TO NODE	2778.0
ROUTE FROM	7	4	3	10		TO NODE	1443.0
ROUTE FROM	8	9				TO NODE	1600.0
ROUTE FROM	8	5	2	3	10	TO NODE	3193.0
ROUTE FROM	9	7	4	3	10	TO NODE	4221.0

1	1	2	44.98[b]	38372.89[c]
2	1	10	14.70	17978.10
3	3	10	396.36	220375.20
4	2	3	141.01	89823.31
5	3	4	214.38	122625.30
6	2	4	109.14	45402.22
7	2	5	210.18	86886.81
8	4	5	0.00	0.00
9	4	7	74.56	23486.18
10	5	7	0.00	0.00
11	5	8	54.96	87221.38
12	5	6	56.76	93858.19
13	6	8	4.88	14342.32
14	8	9	4.03	6448.30
15	7	9	45.51	120426.50

TOTAL TON/KM= 973196.60

[a] Route weighted distance

[b] Link tonnage

[c] Weighted ton-kilometers

..MPSX-V1M7.. FIXED ROUTE LINEAR PROGRAMMING INVESTMENT PROBLEM

SECTION 2 - COLUMNS

NUMBER	.COLUMN.	AT	...ACTIVITY...	..INPUT COST..	..LOWER LIMIT.	..UPPER LIMIT.	.REDUCED COST.
19	EG10102	LL	.	44.98000-	.	NONE	11.78000
20	EP10102	LL	.	85.96000-	.	NONE	25.92500
21	EG10110	LL	.	14.70000-	.	NONE	42.06000
22	EP10110	LL	.	29.40000-	.	NONE	86.48500
23	EG10304	LL	.	214.38000-	.	NONE	155.25500
24	EP10304	BS	246.00000	428.76000-	.	NONE	.
25	EG10205	LL	.	210.38000-	.	NONE	151.25500
26	EP10205	BS	378.00000	420.76000-	.	NONE	.
27	EG10405	LL	.	.	.	NONE	56.76000
28	EP10405	LL	.	.	.	NONE	115.88500
29	EG10407	LL	.	74.56000-	.	NONE	15.43500
30	EP10407	BS	315.00000	149.12000-	.	NONE	.
31	EG10507	LL	.	.	.	NONE	56.76000
32	EP10507	LL	.	.	.	NONE	115.88500
33	EG10508	LL	.	54.96000-	.	NONE	1.80000
34	EP10508	LL	.	109.92000-	.	NONE	5.96500
35	EG10506	BS	560.43750	56.76000-	.	NONE	.
36	EP10506	LL	.	113.52000-	.	NONE	2.36500
37	EG10608	LL	.	4.88000-	.	NONE	51.88000
38	EP10608	LL	.	9.76000-	.	NONE	106.12500
39	EG10709	LL	.	45.51000-	.	NONE	11.25000
40	EP10709	LL	.	91.02000-	.	NONE	24.86500
41	GP10204	BS	103.00000	109.14000-	.	NONE	.
42	GP10508	LL	.	54.96000-	.	NONE	14.80750
43	GP10608	LL	.	4.88000-	.	NONE	64.88750
44	GP10809	LL	.	4.03000-	.	NONE	65.73750
45	GP10709	LL	.	45.51000-	.	NONE	24.25750

APPENDIX C

FINAL RESULTS OF TALLYHO AND FRLP OBTAINED IN SOLUTION #3 (BUDGET = 150)

```
                CSENTRY
 ROUTE FROM    1    2
 ROUTE FROM    1    2    3
 ROUTE FROM    1    2    4
 ROUTE FROM    1    2    5
 ROUTE FROM    1    2    5    6
 ROUTE FROM    1    2    4    7
 ROUTE FROM    1    2    5    8
 ROUTE FROM    1    2    5    8    9
 ROUTE FROM    1   10
 ROUTE FROM    2    3
 ROUTE FROM    2    4
 ROUTE FROM    2    5
 ROUTE FROM    2    5    6
 ROUTE FROM    2    4    7
 ROUTE FROM    2    5    8
 ROUTE FROM    2    5    8    9
 ROUTE FROM    2    3   10
 ROUTE FROM    3    4
 ROUTE FROM    3    2    5
 ROUTE FROM    3    2    5    6
 ROUTE FROM    3    4    7
 ROUTE FROM    3    2    5    8
 ROUTE FROM    3    2    5    8    9
 ROUTE FROM    3   10
 ROUTE FROM    4    2    5
 ROUTE FROM    4    2    5    6
 ROUTE FROM    4    7
 ROUTE FROM    4    2    5    8
 ROUTE FROM    4    7    9
 ROUTE FROM    4    3   10
 ROUTE FROM    5    6
 ROUTE FROM    5    2    4    7
 ROUTE FROM    5    8
 ROUTE FROM    5    8    9
 ROUTE FROM    5    2    3   10
 ROUTE FROM    6    5    2    4    7
 ROUTE FROM    6    5    8
 ROUTE FROM    6    5    8    9
```

```
 ROUTE FROM    6    5    2    3   10
 ROUTE FROM    7    4    2    5    8
 ROUTE FROM    7    9
 ROUTE FROM    7    4    3   10
 ROUTE FROM    8    9
 ROUTE FROM    8    5    2    3   10
 ROUTE FROM    9    8    5    2    3   10
    1    1    2      44.98 b      38322.89 c
    2    1   10      14.70         17978.10
    3    3   10     396.36        223375.20
    4    2    3     157.22        100149.00
    5    3    4     198.17        113353.10
    6    2    4     101.24         42115.87
    7    2    5     234.49         96844.25
    8    4    5       0.00             0.00
    9    4    7      50.45         15891.73
   10    5    7       0.00             0.00
   11    5    8      83.95         65229.14
   12    5    6      61.64         83367.94
   13    6    8       0.00             0.00
   14    8    9      28.14         45323.95
   15    7    9      21.40         59469.14
TOTAL  TON/KM=      8481QC.10
```

```
140.
                TO NODE     852.0 a
                TO NODE    1489.0
                TO NODE    1268.0
                TO NODE    1265.0
                TO NODE    2617.5
                TO NODE    1583.0
                TO NODE    2042.0
                TO NODE    3642.0
                TO NODE    1223.0
                TO NODE     637.0
                TO NODE     416.0
                TO NODE     413.0
                TO NODE    1765.5
                TO NODE     731.0
                TO NODE    1190.0
                TO NODE    2790.0
                TO NODE    1193.0
                TO NODE     572.0
                TO NODE    1050.0
                TO NODE    2402.5
                TO NODE     887.0
                TO NODE    1827.0
                TO NODE    3427.0
                TO NODE     556.0
                TO NODE     829.0
                TO NODE    2181.5
                TO NODE     315.0
                TO NODE    1606.0
                TO NODE    3093.0
                TO NODE    1128.0
                TO NODE    1352.5
                TO NODE    1144.0
                TO NODE     777.0
                TO NODE    2377.0
                TO NODE    1606.0
                TO NODE    2496.5
                TO NODE    2129.5
                TO NODE    3729.5
```

```
                TO NODE    2958.5
                TO NODE    1921.0
                TO NODE    2778.0
                TO NODE    1443.0
                TO NODE    1600.0
                TO NODE    2383.0
                TO NODE    3983.0
```

[a]Route weighted distance

[b]Link tonnage

[c]Weighted ton-kilometers

..MPSX-V1M7.. FIXED ROUTE LINEAR PROGRAMMING INVESTMENT PROBLEM

SECTION 2 - COLUMNS

NUMBER	.COLUMN.	AT	...ACTIVITY...	..INPUT COST..	..LOWER LIMIT.	..UPPER LIMIT.	.REDUCED COST.
19	EG10102	LL	.	44.58000-	.	NONE	14.19440
20	EP10102	LL	.	89.96000-	.	NONE	30.85440
21	EG10110	LL	.	14.70000-	.	NONE	44.47440
22	EP10110	LL	.	29.40000-	.	NONE	91.41440
23	EG10304	LL	.	198.17000-	.	NONE	136.52980
24	EP10304	BS	246.00000	396.33980-	.	NONE	.
25	EG10205	LL	.	234.49000-	.	NONE	172.85000
26	EP10205	BS	378.00000	468.98000-	.	NONE	.
27	EG10405	LL	.	.	.	NONE	59.17440
28	EP10405	LL	.	.	.	NONE	120.81440
29	EG10407	LL	.	50.45000-	.	NONE	8.72440
30	EP10407	LL	.	100.90000-	.	NONE	19.91440
31	EG10507	LL	.	.	.	NONE	59.17440
32	EP10507	LL	.	.	.	NONE	120.81440
33	EG10508	LL	.	83.95000-	.	NONE	22.31000
34	EP10508	BS	331.00000	167.90000-	.	NONE	.
35	EG10506	BS	614.46000	61.64000-	.	NONE	.
36	EP10506	BS	123.54000	123.28000-	.	NONE	.
37	EG10608	LL	.	.	.	NONE	59.17440
38	EP10608	LL	.	.	.	NONE	120.81440
39	EG10709	LL	.	21.40000-	.	NONE	37.77440
40	EP10709	LL	.	42.80000-	.	NONE	78.01440
41	GP10204	BS	103.00000	101.24000-	.	NONE	.
42	GP10508	BS	148.00000	83.95000-	.	NONE	.
43	GP10608	LL	.	.	.	NONE	72.73520
44	GP10809	LL	.	28.14000-	.	NONE	44.59520
45	GP10709	LL	.	21.40000-	.	NONE	51.33520

APPENDIX D

FINAL RESULTS OF TALLYHO AND FRLP OBTAINED IN SOLUTION #4 (BUDGET = 175)

ROUTE	FROM	1	2					
ROUTE	FROM	1	2	3				
ROUTE	FROM	1	2	4				
ROUTE	FROM	1	2	5				
ROUTE	FROM	1	2	5	6			
ROUTE	FROM	1	2	4	7			
ROUTE	FROM	1	2	5	8			
ROUTE	FROM	1	2	5	8	9		
ROUTE	FROM	1	10					
ROUTE	FROM	2	3					
ROUTE	FROM	2	4					
ROUTE	FROM	2	5					
ROUTE	FROM	2	5	6				
ROUTE	FROM	2	4	7				
ROUTE	FROM	2	5	8				
ROUTE	FROM	2	5	8	9			
ROUTE	FROM	2	3	10				
ROUTE	FROM	3	4					
ROUTE	FROM	3	2	5				
ROUTE	FROM	3	2	5	6			
ROUTE	FROM	3	4	7				
ROUTE	FROM	3	2	5	8			
ROUTE	FROM	3	2	5	8	9		
ROUTE	FROM	3	10					
ROUTE	FROM	4	2	5				
ROUTE	FROM	4	2	5	6			
ROUTE	FROM	4	7					
ROUTE	FROM	4	2	5	8			
ROUTE	FROM	4	7	9				
ROUTE	FROM	4	3	10				
ROUTE	FROM	5	6					
ROUTE	FROM	5	2	4	7			
ROUTE	FROM	5	8					
ROUTE	FROM	5	8	9				
ROUTE	FROM	5	2	3	10			
ROUTE	FROM	6	5	2	4	7		
ROUTE	FROM	6	5	8				
ROUTE	FROM	6	5	8	9			
ROUTE	FROM	6	5	2	3	10		
ROUTE	FROM	7	4	2	5	8		
ROUTE	FROM	7	9					
ROUTE	FROM	7	4	3	10			
ROUTE	FROM	8	9					
ROUTE	FROM	8	5	2	3	10		
ROUTE	FROM	9	8	5	2	3	10	

TO NODE	852.5[a]			
TO NODE	1489.0			
TO NODE	1268.5			
TO NODE	1265.0			
TO NODE	2117.5			
TO NODE	1583.0			
TO NODE	2042.0			
TO NODE	3642.0			
TO NODE	1223.5			
TO NODE	637.0			
TO NODE	416.0			
TO NODE	413.0			
TO NODE	1265.5			
TO NODE	731.0			
TO NODE	1190.0			
TO NODE	2790.0			
TO NODE	1193.0			
TO NODE	572.0			
TO NODE	1050.0			
TO NODE	1902.5			
TO NODE	887.0			
TO NODE	1827.0			
TO NODE	3427.0			
TO NODE	556.0			
TO NODE	829.0			
TO NODE	1681.5			
TO NODE	315.0			
TO NODE	1606.0			
TO NODE	3093.0			
TO NODE	1128.0			
TO NODE	852.5			
TO NODE	1144.0			
TO NODE	777.0			
TO NODE	2377.0			
TO NODE	1606.0			
TO NODE	1996.5			
TO NODE	1629.5			
TO NODE	3229.5			
TO NODE	2458.5			
TO NODE	1921.0			
TO NODE	2778.0			
TO NODE	1443.0			
TO NODE	1600.0			
TO NODE	2383.0			
TO NODE	3983.0			

1	1	2	44.98[b]	38322.89[c]
2	1	10	14.70	17978.10
3	3	10	396.36	220375.20
4	2	3	157.22	100149.33
5	3	4	198.17	113353.13
6	2	4	101.24	42115.82
7	2	5	234.49	96844.25
8	4	5	0.00	0.00
9	4	7	50.45	15891.73
10	5	7	0.00	0.00
11	5	8	83.95	65229.34
12	5	6	61.64	52548.02
13	6	8	0.00	0.00
14	8	9	28.14	45023.95
15	7	9	21.40	59449.14
TOTAL	TON/KM=		867280.20	

[a]Route weighted distance

[b]Link tonnage

[c]Weighted ton-kilometers

..MPSX-V1M7.. FIXED ROUTE LINEAR PROGRAMMING INVESTMENT PROBLEM

SECTION 2 - COLUMNS

NUMBER	.COLUMN.	AT	...ACTIVITY...	..INPUT COST..	..LOWER LIMIT.	..UPPER LIMIT.	.REDUCED COST.
19	EG10102	LL	.	44.98000-	.	NONE	14.19440
20	EP10102	LL	.	89.96000-	.	NONE	30.85440
21	EG10110	LL	.	14.70000-	.	NONE	44.47440
22	EP10110	LL	.	29.40000-	.	NONE	91.41440
23	EG10304	LL	.	198.17000-	.	NONE	136.52980
24	EP10304	BS	246.00000	396.33980-	.	NONE	.
25	EG10205	LL	.	234.49000-	.	NONE	172.85000
26	EP10205	BS	378.00000	468.98000-	.	NONE	.
27	EG10405	LL	.	.	.	NONE	59.17440
28	EP10405	LL	.	.	.	NONE	120.81440
29	EG10407	LL	.	50.45000-	.	NONE	8.72440
30	EP10407	LL	.	100.90000-	.	NONE	19.91440
31	EG10507	LL	.	.	.	NONE	59.17440
32	EP10507	LL	.	.	.	NONE	120.81440
33	EG10508	LL	.	83.95000-	.	NONE	22.31000
34	EP10508	BS	331.00000	167.90000-	.	NONE	.
35	EG10506	BS	114.46000	61.64000-	.	NONE	.
36	EP10506	BS	623.54000	123.28000-	.	NONE	.
37	EG10608	LL	.	.	.	NONE	59.17440
38	EP10608	LL	.	.	.	NONE	120.81440
39	EG10709	LL	.	21.40000-	.	NONE	37.77440
40	EP10709	LL	.	42.80000-	.	NONE	78.01440
41	GP10204	BS	103.00000	101.24000-	.	NONE	.
42	GP10508	BS	148.00000	83.95000-	.	NONE	.
43	GP10608	LL	.	.	.	NONE	72.73520
44	GP10809	LL	.	11.93000-	.	NONE	60.80520
45	GP10709	LL	.	21.40000-	.	NONE	51.33520

APPENDIX E

FINAL RESULTS OF TALLYHO AND FRLP OBTAINED IN SOLUTION #5 (BUDGET = 200)

ROUTE	FROM	1	2	3			
ROUTE	FROM	1	2	4			
ROUTE	FROM	1	2	5			
ROUTE	FROM	1	2	5	6		
ROUTE	FROM	1	2	4	7		
ROUTE	FROM	1	2	5	8		
ROUTE	FROM	1	2	5	8	9	
ROUTE	FROM	1	10				
ROUTE	FROM	2	3				
ROUTE	FROM	2	4				
ROUTE	FROM	2	5				
ROUTE	FROM	2	5	6			
ROUTE	FROM	2	4	7			
ROUTE	FROM	2	5	8			
ROUTE	FROM	2	5	8	9		
ROUTE	FROM	2	3	10			
ROUTE	FROM	3	4				
ROUTE	FROM	3	2	5			
ROUTE	FROM	3	2	5	6		
ROUTE	FROM	3	4	7			
ROUTE	FROM	3	2	5	8		
ROUTE	FROM	3	2	5	8	9	
ROUTE	FROM	3	10				
ROUTE	FROM	4	2	5			
ROUTE	FROM	4	2	5	6		
ROUTE	FROM	4	7				
ROUTE	FROM	4	2	5	8		
ROUTE	FROM	4	2	5	8	9	
ROUTE	FROM	4	3	10			
ROUTE	FROM	5	6				
ROUTE	FROM	5	7				
ROUTE	FROM	5	8				
ROUTE	FROM	5	8	9			
ROUTE	FROM	5	2	3	10		
ROUTE	FROM	6	5	7			
ROUTE	FROM	6	5	8			
ROUTE	FROM	6	5	8	9		

ROUTE	FROM	6	5	2	3	10	
ROUTE	FROM	7	5	8			
ROUTE	FROM	7	9				
ROUTE	FROM	7	4	3	10		
ROUTE	FROM	8	5				
ROUTE	FROM	8	5	2	3	10	
ROUTE	FROM	9	8	5	2	3	10

1	1	2	44.98 [b]	20497.34 [c]
2	1	10	14.70	17978.10
3	3	10	396.36	220375.20
4	2	3	157.22	100149.00
5	3	4	198.17	113353.10
6	2	4	114.27	47536.31
7	2	5	247.52	102225.60
8	4	5	0.00	0.00
9	4	7	22.14	12108.35
10	5	7	7.64	10069.52
11	5	8	104.62	61289.56
12	5	6	61.64	45490.25
13	6	8	0.00	0.00
14	8	9	48.81	78095.88
15	7	9	0.73	2027.94
TOTAL	TON/KM=		851156.10	

TO NODE	1092.7[a]
TO NODE	871.7
TO NODE	868.7
TO NODE	1606.7
TO NODE	1418.6
TO NODE	1645.7
TO NODE	3245.7
TO NODE	1223.0
TO NODE	637.0
TO NODE	416.0
TO NODE	413.0
TO NODE	1151.0
TO NODE	962.9
TO NODE	1190.0
TO NODE	2790.0
TO NODE	1193.0
TO NODE	572.0
TO NODE	1050.0
TO NODE	1788.0
TO NODE	1118.9
TO NODE	1827.0
TO NODE	3427.0
TO NODE	556.0
TO NODE	829.0
TO NODE	1567.0
TO NODE	546.9
TO NODE	1606.0
TO NODE	3206.0
TO NODE	1128.0
TO NODE	738.0
TO NODE	1318.0
TO NODE	777.0
TO NODE	2377.0
TO NODE	1606.0
TO NODE	2056.0
TO NODE	1515.0
TO NODE	3115.0

TO NODE	2344.0
TO NODE	2095.0
TO NODE	2778.0
TO NODE	1674.9
TO NODE	1600.0
TO NODE	2383.0
TO NODE	3983.0

[a] Route weighted distance

[b] Link tonnage

[c] Weighted ton-kilometers

..MPSX-V1M7.. FIXED ROUTE LINEAR PROGRAMMING INVESTMENT PROBLEM

SECTION 2 - COLUMNS

NUMBER	.COLUMN.	AT	...ACTIVITY...	..INPUT COST..	..LOWER LIMIT.	..UPPER LIMIT.	.REDUCED COST.
19	EG10102	BS	143.66000	44.98000-	.	NONE	.
20	EP10102	BS	126.34000	89.96000-	.	NONE	.
21	EG10110	LL	.	14.70000-	.	NONE	28.48080
22	EP10110	LL	.	29.40000-	.	NONE	58.76080
23	EG10304	LL	.	198.17000-	.	NONE	153.18980
24	EP10304	BS	246.00000	396.33980-	.	NONE	.
25	EG10205	LL	.	247.52000-	.	NONE	202.53980
26	EP10205	BS	378.00000	495.03980-	.	NONE	.
27	EG10405	LL	.	.	.	NONE	43.18080
28	EP10405	LL	.	.	.	NONE	88.16080
29	EG10407	LL	.	22.14000-	.	NONE	21.04080
30	EP10407	LL	.	44.28000-	.	NONE	43.88080
31	EG10507	LL	.	7.64000-	.	NONE	35.54080
32	EP10507	LL	.	15.28000-	.	NONE	72.88080
33	EG10508	LL	.	104.62000-	.	NONE	59.64000
34	EP10508	BS	331.00000	209.24000-	.	NONE	.
35	EG10506	LL	.	61.64000-	.	NONE	16.66000
36	EP10506	BS	738.00000	123.28000-	.	NONE	.
37	EG10608	LL	.	.	.	NONE	43.18080
38	EP10608	LL	.	.	.	NONE	88.16080
39	EG10709	LL	.	.73000-	.	NONE	42.45080
40	EP10709	LL	.	1.46000-	.	NONE	86.70080
41	GP10204	BS	103.00000	114.27000-	.	NONE	.
42	GP10508	BS	148.00000	104.62000-	.	NONE	.
43	GP10608	LL	.	.	.	NONE	53.07640
44	GP10809	LL	.	48.81000-	.	NONE	4.26640
45	GP10709	LL	.	.73000-	.	NONE	52.34640

APPENDIX F

FINAL RESULTS OF TALLYHO AND FRLP OBTAINED IN SOLUTION #6 (BUDGET = 225)

ROUTE	FROM	1	2						TO NODE 1240.1 [a]
ROUTE	FROM	1	2	3					TO NODE 989.1
ROUTE	FROM	1	2	4					TO NODE 986.1
ROUTE	FROM	1	2	5					TO NODE 1724.1
ROUTE	FROM	1	2	5	6				TO NODE 1304.1
ROUTE	FROM	1	2	4	7				TO NODE 1763.1
ROUTE	FROM	1	2	5	8				TO NODE 3363.1
ROUTE	FROM	1	2	5	8	9			TO NODE 1223.0
ROUTE	FROM	1	10						TO NODE 637.0
ROUTE	FROM	2	3						TO NODE 416.0
ROUTE	FROM	2	4						TO NODE 413.0
ROUTE	FROM	2	5						TO NODE 1151.0
ROUTE	FROM	2	5	6					TO NODE 731.0
ROUTE	FROM	2	4	7					TO NODE 1190.0
ROUTE	FROM	2	5	8					TO NODE 2790.0
ROUTE	FROM	2	5	8	9				TO NODE 1193.0
ROUTE	FROM	2	3	10					TO NODE 572.0
ROUTE	FROM	3	4						TO NODE 1050.0
ROUTE	FROM	3	2	5					TO NODE 1788.0
ROUTE	FROM	3	2	5	6				TO NODE 887.0
ROUTE	FROM	3	4	7					TO NODE 1827.0
ROUTE	FROM	3	2	5	8				TO NODE 3203.8
ROUTE	FROM	3	4	7	9				TO NODE 556.0
ROUTE	FROM	3	10						TO NODE 829.0
ROUTE	FROM	4	2	5					TO NODE 1567.0
ROUTE	FROM	4	2	5	6				TO NODE 315.0
ROUTE	FROM	4	7						TO NODE 1606.0
ROUTE	FROM	4	2	5	8				TO NODE 2631.8
ROUTE	FROM	4	7	9					TO NODE 1128.0
ROUTE	FROM	4	3	10					TO NODE 738.0
ROUTE	FROM	5	6						TO NODE 1144.0
ROUTE	FROM	5	2	4	7				TO NODE 777.0
ROUTE	FROM	5	8						TO NODE 2377.0
ROUTE	FROM	5	8	9					TO NODE 1606.0
ROUTE	FROM	5	2	3	10				TO NODE 1882.0
ROUTE	FROM	6	5	2	4	7			TO NODE 1515.0
ROUTE	FROM	6	5	8					TO NODE 3115.0
ROUTE	FROM	6	5	8	9				
ROUTE	FROM	6	5	2	3	10			TO NODE 2344.0
ROUTE	FROM	7	4	2	5	8			TO NODE 1921.0
ROUTE	FROM	7	9						TO NODE 2316.8
ROUTE	FROM	7	4	3	10				TO NODE 1443.0
ROUTE	FROM	8	9						TO NODE 1600.0
ROUTE	FROM	8	5	2	3	10			TO NODE 2383.0
ROUTE	FROM	9	7	4	3	10			TO NODE 3759.8

1	1	2	44.98 [b]	25778.00	[c]
2	1	10	14.70	17478.10	
3	3	10	356.36	220375.20	
4	2	3	141.01	89823.31	
5	3	4	214.38	122625.30	
6	2	4	101.24	42115.82	
7	2	5	218.28	90149.56	
8	4	5	0.00	0.00	
9	4	7	66.66	20997.88	
10	5	7	0.00	0.00	
11	5	8	67.74	52633.89	
12	5	6	61.64	45490.25	
13	6	8	0.00	0.00	
14	8	9	11.93	14088.00	
15	7	9	37.61	87134.75	

TOTAL TON/KM= 834150.00

[a] Route weighted distance

[b] Link tonnage

[c] Weighted ton-kilometers

..MPSX-V1M7.. FIXED ROUTE LINEAR PROGRAMMING INVESTMENT PROBLEM

SECTION 2 - COLUMNS

NUMBER	.COLUMN.	AT	...ACTIVITY...	..INPUT COST..	..LOWER LIMIT.	..UPPER LIMIT.	.REDUCED COST.
19	EG10102	BS	261.06000	44.98000-	.	NONE	.
20	EP10102	BS	8.94000	89.96000-	.	NONE	.
21	EG10110	LL	.	14.70000-	.	NONE	28.48080
22	EP10110	LL	.	29.40000-	.	NONE	58.76080
23	EG10304	LL	.	214.38000-	.	NONE	169.40000
24	EP10304	BS	246.00000	428.76000-	.	NONE	.
25	EG10205	LL	.	218.28000-	.	NONE	173.29980
26	EP10205	BS	378.00000	436.55980-	.	NONE	.
27	EG10405	LL	.	.	.	NONE	43.18080
28	EP10405	LL	.	.	.	NONE	88.16080
29	EG10407	LL	.	66.66000-	.	NONE	21.68000
30	EP10407	BS	315.00000	133.32000-	.	NONE	.
31	EG10507	LL	.	.	.	NONE	43.18080
32	EP10507	LL	.	.	.	NONE	88.16080
33	EG10508	LL	.	67.74000-	.	NONE	22.76000
34	EP10508	BS	331.00000	135.48000-	.	NONE	.
35	EG10506	LL	.	61.64000-	.	NONE	16.66000
36	EP10506	BS	738.00000	123.28000-	.	NONE	.
37	EG10608	LL	.	.	.	NONE	43.18080
38	EP10608	LL	.	.	.	NONE	88.16080
39	EG10709	LL	.	37.61000-	.	NONE	5.57080
40	EP10709	LL	.	75.22000-	.	NONE	12.94080
41	GP10204	BS	103.00000	101.24000-	.	NONE	.
42	GP10508	BS	148.00000	67.74000-	.	NONE	.
43	GP10608	LL	.	.	.	NONE	53.07640
44	GP10809	LL	.	11.93000-	.	NONE	41.14640
45	GP10709	LL	.	37.61000-	.	NONE	15.46640

APPENDIX G

FINAL RESULTS OF TALLYHO AND FRLP OBTAINED IN SOLUTION #7 (BUDGET = 250)

ROUTE FROM	1	2							TO NODE	585.8 [a]
ROUTE FROM	1	2	3						TO NODE	1222.8
ROUTE FROM	1	2	4						TO NODE	1001.8
ROUTE FROM	1	2	5						TO NODE	998.8
ROUTE FROM	1	2	5	6					TO NODE	1736.8
ROUTE FROM	1	2	4	7					TO NODE	1316.8
ROUTE FROM	1	2	5	8					TO NODE	1775.8
ROUTE FROM	1	2	4	7	9				TO NODE	3336.8
ROUTE FROM	1	10							TO NODE	1223.0
ROUTE FROM	2	3							TO NODE	637.0
ROUTE FROM	2	4							TO NODE	416.0
ROUTE FROM	2	5							TO NODE	413.0
ROUTE FROM	2	5	6						TO NODE	1151.0
ROUTE FROM	2	4	7						TO NODE	731.0
ROUTE FROM	2	5	8						TO NODE	1190.0
ROUTE FROM	2	4	7	9					TO NODE	2751.0
ROUTE FROM	2	3	10						TO NODE	1193.0
ROUTE FROM	3	4							TO NODE	572.0
ROUTE FROM	3	2	5						TO NODE	1050.0
ROUTE FROM	3	2	5	6					TO NODE	1788.0
ROUTE FROM	3	4	7						TO NODE	887.0
ROUTE FROM	3	2	5	8					TO NODE	1827.0
ROUTE FROM	3	4	7	9					TO NODE	2907.0
ROUTE FROM	3	10							TO NODE	556.0
ROUTE FROM	4	2	5						TO NODE	829.0
ROUTE FROM	4	2	5	6					TO NODE	1567.0
ROUTE FROM	4	7							TO NODE	315.0
ROUTE FROM	4	2	5	8					TO NODE	1606.0
ROUTE FROM	4	7	9						TO NODE	2335.0
ROUTE FROM	4	3	10						TO NODE	1128.0
ROUTE FROM	5	6							TO NODE	738.0
ROUTE FROM	5	2	4	7					TO NODE	1144.0
ROUTE FROM	5	8							TO NODE	777.0
ROUTE FROM	5	8	9						TO NODE	2377.0
ROUTE FROM	5	2	3	10					TO NODE	1606.0
ROUTE FROM	6	5	2	4	7				TO NODE	1882.0
ROUTE FROM	6	5	8						TO NODE	1515.0
ROUTE FROM	6	5	8	9					TO NODE	3115.0
ROUTE FROM	6	5	2	3	10				TO NODE	2344.0
ROUTE FROM	7	4	2	5	8				TO NODE	1921.0
ROUTE FROM	7	9							TO NODE	2020.0
ROUTE FROM	7	4	3	10					TO NODE	1443.0
ROUTE FROM	8	9							TO NODE	1600.0
ROUTE FROM	8	5	2	3	10				TO NODE	2383.0
ROUTE FROM	9	7	4	3	10				TO NODE	3463.0

1	1	2	44.98 [b]	26349.23 [c]
2	1	10	14.70	17978.10
3	3	10	396.36	220375.20
4	2	3	141.01	89823.31
5	3	4	214.38	122625.50
6	2	4	109.14	65402.22
7	2	5	210.38	86886.81
8	4	5	0.30	0.30
9	4	7	74.56	23486.38
10	5	7	0.60	0.00
11	5	8	59.84	46495.59
12	5	6	61.64	45490.25
13	6	8	0.00	0.00
14	8	9	4.33	6448.00
15	7	9	45.51	91930.13
TOTAL TON/KM=			823290.43	

[a] Route weighted distance

[b] Link tonnage

[c] Weighted ton-kilometers

..MPSX-V1M7.. FIXED ROUTE LINEAR PROGRAMMING INVESTMENT PROBLEM

SECTION 2 - COLUMNS

NUMBER	.COLUMN.	AT	...ACTIVITY...	..INPUT COST..	..LOWER LIMIT.	..UPPER LIMIT.	.REDUCED COST.
19	EG10102	BS	42.14583	44.98000-	.	NONE	.
20	EP10102	LL	.	89.96000-	.	NONE	1.87417
21	EG10110	LL	.	14.70000-	.	NONE	30.28000
22	EP10110	LL	.	29.40000-	.	NONE	62.43417
23	EG10304	LL	.	214.38000-	.	NONE	167.52583
24	EP10304	BS	246.00000	428.76000-	.	NONE	.
25	EG10205	LL	.	210.38000-	.	NONE	163.52583
26	EP10205	BS	378.00000	420.76000-	.	NONE	.
27	EG10405	LL	.	.	.	NONE	44.98000
28	EP10405	LL	.	.	.	NONE	91.83417
29	EG10407	LL	.	74.56000-	.	NONE	27.70583
30	EP10407	BS	315.00000	149.12000-	.	NONE	.
31	EG10507	LL	.	.	.	NONE	44.98000
32	EP10507	LL	.	.	.	NONE	91.83417
33	EG10508	LL	.	59.84000-	.	NONE	12.98583
34	EP10508	BS	331.00000	119.68000-	.	NONE	.
35	EG10506	LL	.	61.46000-	.	NONE	14.60583
36	EP10506	BS	738.00000	122.92000-	.	NONE	.
37	EG10608	LL	.	.	.	NONE	44.98000
38	EP10608	LL	.	.	.	NONE	91.83417
39	EG10709	BS	758.00000	45.51000-	.	NONE	.
40	EP10709	LL	.	91.02000-	.	NONE	1.34417
41	GP10204	BS	103.00000	109.14000-	.	NONE	.
42	GP10508	BS	148.00000	59.84000-	.	NONE	.
43	GP10608	LL	.	.	.	NONE	55.28792
44	GP10809	LL	.	4.03000-	.	NONE	51.25792
45	GP10709	LL	.	45.51000-	.	NONE	9.77792

VITA

Gaafar Hassan Elshaygi was born in El Kamlin, a small town in the Sudan, on 1947. He received his elementary and intermediate education in schools of his home town. He graduated from Hantoub Secondary School in 1967. He was awarded the degree of Bachelor of Arts with honors in geography from the University of Khartoum in May 1972.

In January 1967, Mr. Elshaygi entered Indiana University at Bloomington where he received his Master of Arts degree with a major in geography in February 1978. He started his Ph.D. program at Indiana University then moved to Knoxville, Tennessee, in May 1979, to continue working on his doctorate at The University of Tennessee. The Ph.D. degree was completed in June 1983.

While in the Sudan, Mr. Elshaygi worked as a high school teacher in the Ministry of Education for a short time, Assistant Archivist in the Sudan Central Records Office, and Teaching Assistant at Omdurman Islamic University. He completed a two-months training course in public administration at the Institute of Public Administration in Khartoum.

While at The University of Tennessee, Mr. Elshaygi worked as a Teaching Assistant at the Geography Department for six months. He was also an employee of public relations in the Pavillion of Saudi Arabia in the 1982 Worlds Fair in Knoxville, Tennessee. Mr. Elshaygi is married and has two daughters, Maisoon and Samah.