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A program to develop improved guidelines for evaluating low volume road investments in developing countries. It focuses both on project level decisions and on planning, programming and budgetary decisions for the road network as a whole. The first year of the program consisted of four tasks --1) modification of an existing project evaluation model--the Highway Cost Model--to reflect recent research in road deterioration and user costs; 2) demonstration of the usefulness of the model in assessing road construction projects in East Africa; 3) building instututional linkages for subsequent use of the model within the highway department of an East African country; and 4) the development of a framework for making planning, programming, and budgetary decisions for road networks.

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YEARLY PROGRESS REPORT

Evaluation Framework for Transportation Planning in Developing Countries

Prepared for

The Office of Science and Technology
Agency for International Development
United States Department of State

by

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YEARLY PROGRESS REPORT

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Yearly Progress Report

STATISTICAL SUMMARY

Title:	Evaluation Framework for Transportation Planning in Developing Countries
Contractor:	Massachusetts Institute of Technology 77 Massachusetts Avenue Cambridge, Massachusetts 02139
Principal Investigator:	Dr. Fred Moavenzadeh Professor of Civil Engineering Room 1-173 Massachusetts Institute of Technology
Sponsor:	Agency for International Development New State Department Building Washington, D.C. 20523
Project Monitor:	Mr. John Fry Office of Science and Technology Agency for International Development
Duration:	June 30, 1974 to June 29, 1977
Contract Amount:	$397,886.00
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Yearly Progress Report

NARRATIVE SUMMARY

Summary of Goals

The goal of the program is to develop improved guidelines for evaluating low volume road investments in developing countries. The work focuses both on project level decisions and on planning, programming, and budgeting decisions for the road network as a whole.

The first year of the program consisted of four tasks -- (1) modification of an existing project evaluation model -- the Highway Cost Model -- to reflect recent research in road deterioration and user costs; (2) demonstration of the usefulness of the model in assessing road construction projects in East Africa; (3) building institutional linkages for subsequent use of the model within the highway department of an East African country; and (4) the development of a framework for making planning, programming, and budgeting decisions for road networks.

Summary of Progress

MIT has developed a working agreement with the Ethiopian Highway Authority (EHA) for a joint program in highway planning. The agreement extends over a two-and-one-half-year period and covers work in project evaluation, network planning, and programming and budgeting. The text of this agreement is included in this Report as Appendix A. The objective of the collaborative program is to improve the capabilities of the EHA's Planning and Programming Division. The first phase of the program is nearing completion, and a member of the EHA staff will be returning to

Ethiopia in the near future, having completed a term of study at MIT in the area of highway project evaluation.

MIT is completing arrangements for a workshop on highway planning and project evaluation to be held in Addis Ababa during September 1-3 of this year. The purpose of this workshop is to bring together a group of East African highway officials for a discussion and review of new methodologies for project evaluation. The program will include the results of the work conducted under MIT's contract with AID as well as other recent work in the area. The proposed program for this workshop is attached as Appendix B.

MIT has completed revisions to a project planning model known as the Highway Cost Model. The purpose of the model is to evaluate alternative design, construction and maintenance strategies for low volume roads. The revisions reflect the results of recent field work in Kenya by the Transportation Road Research Laboaratory in collaboartion with the International Bank for Reconstruction and Development, as well as the specific requirements of the Ethiopian Highway Authority. MIT will be installing the model on the EHA computer this August, and has been training a member of the EHA staff in its use and maintenance.

MIT has completed a detailed study of a section of the Tanzania-Zambia highway to demonstrate the capabilities and usefulness of the model, and has employed the model on a number of other projects, including the Yala-Busia in Kenya and the Asela-Dodela and Ghian-Jimma roads in Ethiopia.

MIT has completed the preliminary development of a framework for evaluating investment strategies for the road network as a whole. This framework accounts for dependencies between projects in terms of

their impact on utilization patterns over the entire network. It also accounts for budgetary and resource constraints which affect the level or pattern of transport investment.

Summary of the Report

The Progress Report consists of four parts, each dealing with a separate aspect of the work described in the Project Proposal, "An Evaluation Framework for Transporation Planning in Developing Countries".

Part I of this report, "Institutional Relationships", describes the contacts MIT has established with the Ethiopian Highway Authority and other International Agencies for undertaking the research and disseminating the results.

Part II, entitled "The Highway Cost Model: General Framework", includes a separate attachment to this report, which describes an analytic model for use in evaluating design, construction, and maintenance standards for low volume roads.

Part III, entitled "The Highway Cost Model: Application to Case Studies", includes a separate attachment, which illustrates the use of the model on a road which has been subject to serious deterioration -- the Dar-Es-Salaam-Morogoro section of the Tanzania-Zambia Highway.

Part IV of this report, "Network Evaluation Methods", describes the preliminary design of a network model for use in planning, programming and budgeting of improvements for the road network as a whole.

Each part of the report has been prepared so as to be responsive to the specific task statements for the first year of this contract. These statements are provided at the head of each part.

I. Institutional Relationships

Requirement:

"The Contractor shall recommend to A.I.D., Office of Science & Technology (TA/OST) an African LDC with which the Contractor proposes to cooperate in implementing the research project. The recommendation shall be based on the Contractor's on-site evaluation of availability in the LDC of appropriate data and project, network, and regional/national information, including some from recently completed highway projects; commitment of LDC planning and transport ministries and highway departments and availability of qualified and cooperative personnel; potential for extrapolation of methodology developed to other LDC's; and concurrence of USAID in selection of the host country and their commitment to cooperation to the extent their staff resources permit.

MIT has established a joint program of research with the Ethiopian Highway Authority (EHA) in the area of highway planning and project evaluation. The stated goal of the program is to improve the project evaluation, network planning, and programming and budgeting capabilities of the EHA's Planning and Programming Division. This is to be accomplished by undertaking joint research in each of these areas; and by actively implementing the most useful results in the EHA.

The agreement with EHA was reached in the following manner: under the terms of the contract with AID, Dr. Moavenzadeh and his staff traveled to Ethiopia, Kenya, and Tanzania in August 1974 to determine whether working agreements could be established in any of these countries. In each case contacts were made with the local AID mission and with government transport officials to determine first whether there was interest in the effort, and second, whether there were sufficient technical resources to support the program.

Based on the conclusions of that trip, Dr. Moavenzadeh returned to East Africa in November 1974 with Messers. Fry and Stearns of AID. During this trip the EHA approved the concept of the study, and agreed in principle

to undertake the work jointly with MIT. The details of this arrangement were worked out in discussions in Addis Adaba during the early part of January 1975 between staff members of the EHA and MIT. The results of these meetings were confirmed in a letter of understanding from Dr. Moavenzadeh to the General Manager of the EHA in late January (Appendix A).

This proposed program has been divided into the following three phases: phase one will concentrate on project evaluation, phase two on planning for the highway network as a whole, and phase three on programming and budgeting. All three phases will include a review of existing procedures, the development of new ones, and the training of EHA personnel in their use and applicability. The objective of the program will be to demonstrate both the advantages and limitations of the various approaches to project evaluation and selection, and to put them into a coherent framework for use by the EHA.

The project evaluation phase is scheduled to run from the beginning of February 1975 through the end of August 1975. An EHA staff engineer is currently at MIT pursuing course work and individual study in project evaluation methods. As discussed elsewhere, EHA and MIT have jointly identified several projects which illustrate the range of project types for which the EHA has responsibility and for which feasibility studies have recently been completed. These studies are providing the basis for a critical review of EHA procedures and the demonstration of alternative approaches.

The results of this first phase are to be presented to the EHA staff and an international audience at a conference to be held in Addis Adaba during September 1-3, 1975. The conference will cover project evaluation methods and related topics, including the choice of design and maintenance

standards, and the potential for labor substitution in construction. Those attending will include individuals from highway organizations in East Africa, the International Labor Organization, the World Bank, the Transportation and Road Research Laboratory, AID, and MIT. A copy of the program for the conference is attached as Appendix B.

The second phase of the work program -- in the area of network planning -- will start in September of 1975. The past experience and future development of the Ethiopian highway network will provide a basis for this research. As in the previous phase, a member of the EHA staff will come to MIT to study for a period of approximately five months. MIT will return to Ethiopia in June 1976 to present this work to EHA and to review the overall results of the program.

The optional third phase of the program -- programming and budgeting -- is contingent upon AID's continued funding of MIT's work.

II. The Highway Cost Model: General Framework

Requirement:

> "The Contractor shall modify [a project planning tool known as the] Highway Cost Model . . . by extending its capability related to the choice of technology and time staging of investments in road construction. In making these modifications, significant reliance shall be placed upon data currently being made available by the International Bank for Reconstruction and Development from the TRRL-IBRD study in Kenya.

MIT has completed its revisions to the Highway Cost Model, and will be implementing it for the Ethiopian Highway Authority during September 1975. Implementation work has included training of a member of the EHA staff in the use and maintenance of the model, as well as modifications to make the model compatible with Ethiopian computational facilities.

The basic strucutre of the model and its relationships are described in a report entitled "The Highway Cost Model: General Framework" which is attached as a separate report.

III. The Highway Cost Model: Application to Case Studies

Requirement:

"The Contractor shall identify case studies for application of the Highway Cost Model in the host country and calibrate it to local conditions. The identification of case studies shall be accomplished through consultation with international consulting firms who have had significant work experience in the host country and other experts as necessary."

In order to demonstrate the usefulness of the model over an extended range of conditions, and after appropriate consultations with AID, MIT decided to study projects in three East African countries -- Ethiopia, Kenya, and Tanzania. The specific projects included in this work were selected on the basis of discussions with EHA, AID/REDSO/EA, and IBRD, and reflect a spectrum of project types, design standards and traffic conditions (table 1). The status of the Case Studies is as follows:

The Tanzania-Zambia highway study is completed, and is attached as a separate report, "The Highway Cost Model: Application to the Dar-es-Salaam-Morogoro Section of the Tanzania -Zambia Highway. The Yala-Busia Road in Kenya is analyzed in Chapter 5 of the attached report, The Highway Cost Model: General Framework. Results for both the Asela-Dodola and Ghian-Jima roads are currently being analyzed and will be presented at the September conference in Addis Adaba.

HCM CASE STUDIES

In Progress and Pending

COUNTRY	PROJECT TITLE	LENGTH (Km)	SUBJECT	FEASIBILITY STUDY PREPARED BY	REMARKS
I. Ethiopia	(A) Asela-Dodola	122	Upgrading and new construction -- bituminous surfaced feeder road	SAUTI	All Ethiopian projects chosen by and undertaken at the request of the Chief, Planning & Programming Division
	(B) Ghion-Jima	220	Bituminous surfacing of existing gravel road (upgrading)	Planning & Programming Division (EHA)	
II. Tanzania	(A) Tanzania-Zambia Road (Section 1: Dar-Es-Salaam-Morogoro 186 km)	1920	Realignment and upgrading to asphaltic concrete surface	Stanford Research Institute	Final Design by De Leuw Cather Inc. This section totally funded by USAID
III. Kenya	(A) Yala-Busia Road	15	New construction	Data provided by the World Bank	

TABLE 1

IV. Network Evaluation Methods

Requirement:

> "The Contractor shall develop a framework for evaluating network road construction. He shall adapt a computer program to evaluate multiple alternatives for road links in a network to determine both the optimal period and scale of construction."

(1) Introduction

Purpose of the Model

Investment in the development and upgrading of a low volume road network is one mechanism by which the government of a less-developed country may promote economic and social development. Investment may be programmed by a development planner, either in new network components, upgrading or reconstructing parts of existing network links, or maintaining existing and future facilities. Since changes in one part of a network modify the costs and benefits not only of the modified component or link, but the economics of the network as a whole, decisions on investment alternatives should be based on an evaluation of the integrated operation of the entire road network.

This is a rather complex problem, usually solved on a highly simplified basis in a manner which automatically generates an "optimal" solution. Such an approach does not provide the planners with sufficient technical data and alternatives for the integration of social and political factors with economic forecasts. Nor does it utilize the accuracy and detail that exist in a variety of evaluation tools useful for comparing investment alternatives for a single link. This study approaches network evaluation as an extension of the approach of comparing in detail promising link alternatives by considering the integration of combinations and timings of link alternatives as investment strategies on the network. It is aimed

at providing transportation planners in less developed countries with an easily applied network evaluation tool, building upon the detailed simulation capabilities of the Highway Cost Model for the preparation of data on link behavior.

The Highway Cost Model provides a detailed, accurate framework for assessing the costs and benefits associated with the operation and development of links in a low volume highway network. Initial construction and reconstruction alternatives, with alternative timings for capital investments, may be compared easily and conveniently. Development alternatives or strategies, however, must be described completely, on a year by year, project by project basis over the analysis period for each alternative. Output provides detailed user, construction and maintenance costs by year, and net present value throughout the analysis period, for comparison of alternatives.

Planning and Budgetary Implications

Each less developed country has a network of roads and tracks on which it may invest development or operating funds. In general, investment opportunities far exceed available funds. The problem, then, is to identify the most worthy investments among alternative link developments, and to adjust their timing to live within budgetary, manpower, and investment distribution constraints. As there are a very large number of possible investment options, each with certain costs and benefits to the various parties utilizing the network, a technique for ranking alternative investments, subject to social constraints (economic growth, employment, income distribution, etc.), is required. A simple algorithm for determining and ranking acceptable alternatives is proposed here. This model deals with the network at approximately the same level of detail as the Highway Cost Model,

incorporating it into its processing.

Objectives

The proposed model is intended to provide the decision makers in an LDC with a tool for selecting an investment program and operating policy best suited to its development plans and economic and political constraints. It will present the consequences of potential investment alternatives in a concise form, based on the input of HCM link strategies. The relative timing of these link strategies will be allowed to vary within bounds, and patterns of network strategies generated. These network strategies which do not satisfy the investment constraints will be eliminated, and, for those remaining, year by year benefits will be determined considering the users' consumer surplus, based on HCM operating costs and the opportunity costs of cargo, less maintenance and construction costs. Incremental benefit-cost analysis may then be used to rank the feasible alternatives.

The proposed network evaluation method is divided into four processes: link strategy evaluation, generation of feasible alternative network strategies, evaluation of the behavior of the base network, and evaluation of promising alternative network strategies. Feasible alternatives are those which do not exceed budgeting and resource constraints, while promising alternatives are feasible alternatives with a high social priority rating. Evaluation includes traffic assignment and prediction of owner and user costs and benefits, including construction and maintenance costs, all of which change on a year by year basis with changes in network configuration and characteristics. Monetary and resource budgets may be used to constrain the search among potential alternatives.

(2) Background

2.1 Evaluation Measures and Techniques

There are several evaluation measures available for ranking transport investment alternatives. They typically convert all quantities to monetary worth and ignore non-quantifiable factors. Economic analysis is typified by the Harvard-Brookings Macroeconomic model for evaluating network alternatives in Colombia [1] and Tarborga's work with the Chilean Transport Network [2] which represent impacts on the economy caused by network changes. If financial analysis is used, implying the value of an investment project is independent of its effects on the economy, the focus is on the quantities and costs of resources consumed. That is, it is primarily concerned with budget constraints, and not with the economic impacts of transport investment projects.

The evaluation measures used in such analyses are normally classified into four types, as follows.

i. Standard Benefit-Cost Analysis: In this simple case, the future costs and benefits are discounted to a common time (usually the present), and compared, either by benefit-cost ratio, internal rate of return, or net present value. This approach implies that benefits and costs are linearly additive and that money is a valid measure for all quantities, the unit costs upon which have been agreed. Its objective is to maximize monetary profits over time.

ii. Consumer Surplus: This technique recognizes the non-linearity of user benefits over costs, recognizing utilities, or the real economic value of user benefits. As a general rule, the aggregation of individuals and therefore the general public have a diminshing marginal utility for benefits, as shown by decreasing volumes willing to pay higher costs. The difference

between the willingness to pay and what has actually been paid is the consumer surplus. This method also attempts to maximize profits, but recognizes that benefits often have a real value greater than their price.

iii. Decision Analysis: This approach includes procedures to quantify an individual's utility over uncertainty, using non-linear functions, assessing the utility or real value of all possible outcomes. By maximizing expected values of utility, a sequence of choices or alternatives over time is generated.

iv. Multiattribute-Multiobjective Analysis: This procedure attempts to account for the non-linear, non-additive nature of individual or group utility functions over several attributes and objectives. Once the multiattribute utility functions are defined, the evaluation proceeds in similar fashion to that of the consumer surplus.

2.2 Review of the Literature

The problems associated with the choice of a transport investment strategy are complex in theory, and depend largely upon whose point of view is considered paramount: government, the private sector, or external development agencies. Various approaches to its solution emphasize some aspects and ignore others. A number of computational techniques have been employed in these approaches in an attempt to solve either link or network associated problems; however, none now available can satisfy all the constraints or represent accurately the interdependencies.

Models may be divided into two categories: those dealing with the selection or evaluation of a link investment strategy, and those involving

network strategies. The work done in the category of link investment strategies, or project design, is considerable. Most work deals with the deterministic problems. Wohl and Martin [3] deal with project design, recognizing future impacts of immediate investments but essentially ignoring any timing questions. Tarplay and Drake [4], Thygeson [5], Winfrey [6], and Marglin [7] introduce benefit-cost analysis and develop fairly simple timing models which recognize that substantial benefits may be achieved by considering postponement of investment.

An extensive review of the existing models for network related problems has shown that a great deal of the current approaches apply prescriptive optimization algorithms to fairly simplified problem structures; or massive, complex simulation models which have no concern for the search problem of a combinatorially large solution space.

Furthermore, the appraoches may be divided into three categories, according to the selection criteria applied: (1) capital budgeting models, which assume all benefits are exogenously specified and single-valued, and select the best investment subject to capital (budgetary) constraints; (2) network flow models, which can account for network dependencies and internally predict the flows, and hence, the costs and benefits (these have been generally limited to linear flow models); recent developments in branch and bound techniques have placed fewer constraints on the form of the flow model; (3) the growth models, which are the most complex, adding the constraints of long-run supply-demand dependencies, in addition to normally using a complicated network flow-simulation procedure.

2.2.1 Capital Budgeting Models

Marglin [7], in his classic study, appears to be the first to deal with the selection problem, but admittedly deals only with dependencies caused solely by budget constraints. He tries to find the budget allocation which maximizes the sum of project net present value and the net present value of slack, subject to the condition that the sum of project outlays in each period not exceed the period's budget.

Weingartner [8] thoroughly explores mathematical programming and the capital budgeting problem; he also presents a survey of a number of techniques useful for producing solutions to the budgeting problem.

Mori [9] explores the use of dynamic programming for multiple project selection and introduces capital budget constraints. He tried to find an optimal schedule or sequence of highway investments, to maximize the benefits for all projects in each period, B_i, for P periods, stated as:

$$\text{maximize} \quad Z = \sum_{i=1}^{P} B_i = \sum_{i=1}^{P} g_{ij} \, (x_{ij}) \tag{2-1}$$

where x_{ij} = the amount allocated for project j in period i.
g_{ij} = benefit rates.

The capital budgeting constraint in each period is

$$X_i \geq \sum_{j}^{i} x_{ij} \tag{2-2}$$

where X_i is the budget available at period i.

The program first computes the initial return functions for each individual project -- a return function for a single project is generally nothing more than a tabulation of the benefits that are associated with each stage of construction. Afterwards, it computes the most advantageous investment program for each level of investment (i.e., the return function) for more and more of the projects taken together. During this entire process the return function developed for each set of projects (first two, then three, etc.) is printed out. This technique permits: (1) examination of many stages for each project proposed as an addition to the road network (however, this technique is limited by practicality to only two or three stages); (2) analysis over multiple time periods; (3) inclusion of budget limitations; and (4) consideration of situations where system costs and benefits change over time.

Brademeyer [10] explores the capital budgeting problem in association with the selection of a maintenance policy for the single link case under conditions of uncertainty with respect to traffic and road condition. He assumes that all necessary inputs are known, except for the traffic stream (the others are computed by a rational probabilistic pavement deterioration and maintenance model). Then, computes the "best" maintenance strategy as follows:

1. Given the initial traffic rate λ_1, it assumes an initial growth rate of r_1 holds for the design horizon. It evaluates the "best" maintenance sequence given these assumptions, by:

$$S_1 = (M_{11}, M_{21}, M_{31}, \ldots, M_{N1} \quad \lambda_1, r_1) \tag{2-3}$$

and implements decision M_{11} at time t_1. Here M_{1j} denotes any possible member of the set of maintenance options.

2. As traffic information becomes known, it revises assumed traffic growth rates accordingly, and computes the "best" maintenance sequence given the revised values. Of course, maintenance decisions that were previously implemented cannot be altered. Thus, in the second period, the decision would be implemented from the "best" sequence given by:

$$S_2 = (M_{11}, M_{22}, M_{32}, \ldots M_{N2} \quad \lambda_1, \lambda_2, r_2) \tag{2-4}$$

where $r_2 = (\lambda_2 - \lambda_1)/\lambda_1$

Clearly, if the revised r_i is equal to r_{i-1}, S_{i-1} is still optimal and S_i need not be evaluated.

3. Iterating over step 2 until the design horizon is reached, yields the "best" sequence, given the input traffic stream, as:

$$S_N = (M_{11}, M_{22}, \ldots M_{NN} \quad \lambda_1, \lambda_2, \ldots \lambda_N, r_N) \tag{2-5}$$

The output of the model will consistsof a conditioned sequence of maintenance efforts which will provide "optimal" riding surface conditions, given some utility function and the traffic stream. The concept of maintenance action could easily be expanded to include all upgrading or construction activities.

There are a great many other capital budgeting models, far too numerous to completely identify here.

2.2.2 Network flow models

In these formulations, the primary characteristic is that the costs and benefits are not exogenously specified, fixed quantities, but depend on some prediction mechanism. In some cases, it can be internal (as in linear flow models), and in others, predictions can come from a completely separate model. Notably, they all deal with a deterministic and fixed demand structure.

2.2.2.1 Traffic assignment approaches

Beckman, McGuire, and Winsten [11] considered a transport network consisting of N nodes, connected by directed arcs, with a single type of homogeneous traffic flowing on it. The routing and traffic volumes are determined using an algorithm which: (1) Starts with an initial demand $D_{1,k}$ on each origin-deatination pair (1-k), and the flows x_{ij} over the links ij. (2) Computes the travel cost or time $C_{ij} = a+bx_{ij}$, where a and b are constant. (3) Finds the minimum cost path $C_{1,k}$ for each origin-destination pair (1-k). (4) Generates a new demand $D'_{1,k} = f-g\ C_{1,k}$, where f and g are constant, to account for cost elasticity. (5) Generates a weighted sum of the new and the old demand, as $\alpha D'_{1,k} + (1-\alpha)D_{1,k}$; $(0<\alpha\leq 1)$. (6) Then for assignment of the flows on the links imposes the conservation conditions

$$\sum_{j=1}^{N} (x_{ij} - x_{ji}) = \begin{cases} D_{1,k} \text{ (origin)} \\ -D_{1,k} \text{ (destination)} \\ 0 \text{ (otherwise)} \end{cases} \tag{2-6}$$

(7) Repeats the same calculations for all O-D pairs. This processes then iterates on the flows between each O-D pair, oscillating with α, and if α

is progressively decreased during the iterations, convergence should be satisfactory. Note that if b is close to or equal to zero, α can be set to 1.0 and iteration is not necessary.

Manheim and Martin [12] have proposed an algorithm which requires as input those variables generally associated with traffic assignment -- interzonal transfers, network description, and volume-delay characteristics -- along with volume and generation rate characteristics.

The algorithm works through five basic phases:

1) The random selection of a zone pair

2) The determination of the minimum time path between the zone pairs.

3) The use of a generation rate characteristic to determine the potential volume between the zone pairs

4) The addition of a small increment of the potential volume to the minimum time path

5) The use of volume-delay characteristics to update the travel times on the links of the minimum path due to the increase in traffic volume.

The produced outputs are: link volume and travel time, interzonal assigned volume, and interzonal potential volume.

2.2.2.2 Linear programming approaches

Isard [13] developed a model considering aggregately the shipment of commodities between regions. Shipments are considered to be direct between origins and destinations, ignoring rerouting and transshipment possibilities as well as capacity constraints on the links. In each region, many commodities are produced, some of which are pure intermediates, some

of which are pure finished products, and some of which can be consumed either as intermediates (by industry) or as finished products (by households). An item which serves as an intermediate and finished product is treated as two commodities -- a dummy activity is used to transform an intermediate into a finished product.

The author assumes three types of constraints: on the use of resources, on intermediates, and on finished products. The model uses as its objective function regional income maximization:

$$\text{maximize } Z = \sum_{\ell=1}^{L} \sum_{j=1}^{J} C_j^{\ell} x_j^{\ell} \tag{2-7}$$

subject to the following constraints:

$$\sum a_{kj}^{\ell} x_j^{\ell} + \sum_{\substack{m=1 \\ m \neq \ell}}^{M} \sum_{\ell=1}^{L} a_{kj}^{m \to \ell} x_j^{m} \leq R_k^{\ell} \qquad \begin{matrix} k=1,K \\ \ell=1,L \end{matrix} \tag{2-8}$$

where:

a_{kj}^{ℓ} is the amount of the kth commodity required per unit level of the jth activity in region ℓ

x_j^{ℓ} is the level of production activity for the jth commodity in region ℓ

$a_{kj}^{m \to \ell}$ is the amount of the kth commodity shipped from region m to region ℓ per unit level of the jth activity in region ℓ

R_j^{ℓ} is the income per unit level of the jth activity in region ℓ

This model is very general, dealing with regional economics more than the evaluation of alternative improvements to the network.

Taborga [2] developed a model to study the optimal transportation policy in Chile. The specified network is general, and of the type associated with multicommodity flow patterns. Transportation is considered

on a national level, with production as well as commodity distribution being considered. Therefore, although it was developed for a railroad network, it is rather more a regional economic model than a network flow model. The flow constraint is introduced as:

$$\sum_k [\sum_j x^k_{ijt} - x^k_{jit} - f^k_i - y^k_i + E^k_i + V^k_i] = 0 \qquad (2\text{-}9)$$

where:

x^k_{ijt} is the flow on link ij of commodity k by mode t

f^k_i is the production of commodity k entering mode i

y^k_i is the imports of commodity k entering at i

E^k_i is the exports of commodity k leaving at i

V^k_i is the consumption of commodity k at i

One of the commodities is an "empty commodity", allowing the study of trip backhaul and the accumulation of vehicles at the nodes. There is also a node capacity constraint:

$$\sum_k \sum_j (x^k_{ijt} - x^k_{jit}) + S^t_i = 0 \qquad (2\text{-}10)$$

where the slack variable S^t_i permits empty vehicles to accumulate at node i. New capacity can be implemented in the model by means of the constraint:

$$\sum_k x^k_{ijt} - U\, k_{ijt} \leq 0 \qquad (2\text{-}11)$$

where K_{ijt} is a dummy variable taking value 0 or 1 indicating respectively the non-existence of existence of a network link

U is a very large positive number

Therefore, if $K_{ijt} = 0$, the flow over the link will be zero; if $K_{ijt} = 1$, the flow over the link is unbounded. There is also a budget constraint:

$$\sum_{ij} K_{ijt} P_{ijt} \leq B_t \tag{2-12}$$

where P_{ijt} is the unit cost of adding capacity to link ij in mode t

B_t is the fixed cost for network construction and improvement in mode t

Rolling stock capacity as well as link capacity are taken into account; as is investment in productive capacity. The objective function tries to

$$\text{minimize } Z = \sum_k \sum_{i,j} C^k_{ij} x^k_{ij} + \sum_{ij} K^1_{ij} P^1_{ij} + \sum_{ij} K^2_{ij} W_{ij} - \sum_k \sum_i (f^k_i - f^k_{io}) S^k_i \tag{2-13}$$

where:

C^k_{ij} is the unit cost of shipping commodity k over link ij

W_{ij} is the cost or disutility of not constructing link ij

S^k_i is the social gain or utility weight associate with a peruunit increase in the production of commodity k at mode i

K^1_{ij} is a dummy variable equal to 1 if the link ij is constructed, zero otherwise

K^2_{ij} is a dummy variable equal to 1 if the link ij is constructed, zero otherwise

2.2.3 Dynamic Programming and/or Branch and Bound Algorithm Approaches

Hershdorfer [14] applied a branch and bound algorithm, [illegible] to the single period, link addition problem, developing [illegible] a linear programming flow model to determine the measure of effectiveness of network changes. A general network of nodes and directed arcs is established, with demand specified between origin-destination pairs. Each "commodity" may be the flow from a single origin to several destinations, or from several origins to one destination, with flow and capacity constraints for existing and additional links. The objective function computes the minimum additional construction necessary to reduce travel costs.

Roberts[15], at the same time but acting independently, explored the use of the same branch and bound algorithm coupled with a heuristic backward-stepping. time-sequencing algorithm for the multi-period problem.

Bergendahl[16], in an approach similar to Roberts', used a linear programming flow model for predicting the flow pattern of any investment plan at any stage, using dynamic programming to search for the optimal time-staged investment sequence.

Meyer and Straszheim[17] developed a model which minimizes the sum of costs for construction of new links and vehicle operations on the network, subject to the following constraints: (1) all demands and supplies of each commodity type must be met by flow over the network, in which flows are conserved at each node; (2) there is no flow over nonexistent links; (3) the amount of funds committed to construction of new links must not exceed the available budget; and (4) partial construction of a project is not allowed. They have introduced a multitime period staging formulation, defining the appropriate investments over time. They assume that the network at any given stage i is a subset of the network at stage i+1, and there-

fore employ a dynamic programming approach. However, this means that traffic patterns in the last planning period are the only ones that affect the selection of the highly important final plan; today's volumes merely determine which links of this final plan to build early. There is, therefore, an element of commitment to the final plan inherent in this approach.

2.2.4 Simulation model approach

There are a number of heuristic approaches for the network flow problem, concentrating primarily on the link addition, capacity expansion, single period problem, using simulation models. Most of the present work has been done for railroad networks, although the approach is general. Allman[18] developed a model which simulates the real world movement of cars and trains through a network, given a fixed train schedule, instead of the usual problem of calculating an optimal train schedule for a fixed traffic pattern. The major outputs of the model are train hauling costs, yard classification costs, and mean transit times. As Folk[19] points out, a lot of simulation models have been developed to solve the needs of different North American railroads.

2.2.5 Pecknold's approach

Pecknold[20] recognizes that investments are usually implemented as a series of staged sequential increments to a fairly extensive existing system, and that there is substantial uncertainty over the future demands for those investment increments. He has developed a stochastic, sequential,

time-staging model capable of handling supply-demand interdependencies, network connectedness, budgetary constraints, and long-run activity system dependencies on transport investments. The use of a descriptive non-analytic simulation model for transport flows, which recognizes both uncertainty and the multistage nature of investment alternatives, results in an extensive multistage decision tree of extreme dimension. Pecknold introduces approximating procedures, called pruning rules and terminal evaluation functions, to heuristically reduce the solution space, making application of the sequential decision model in extensive form feasible for large network problems. Both the model and the approximating procedures are implemented as a series of computer programs, which simulate the supply-demand network flow patterns on a two-node network at each stage as well as producing demand shifts over the long-run for conditions of a stochastic demand formulation. He points out that the general framework can be applied to problems of small scale without incorporating the pruning rules and terminal functions. In large project design problems, or even modest network problems, these functions are required to reduce the solution space. His results indicate that good heuristic investment patterns can be developed without searching the entire tree.

2.2.6 Foster's approach

Foster[21] developed a new technique, designed to permit the evaluation of individual projects, retaining the level of detail available from a full-scale mathematical model. His aim was to produce an inexpensive and easy-to-use technique, capable of producing substantially the same results as a standard model, using newly developed algorithms which short-cut the

full-scale model by forecasting changes in the existing travel pattern resulting from the influence of a particular project. This model would normally be run for the minimum network investment, providing a basis for evaluating larger investments. It would then evaluate subsequent variations on the basic network by calculating changes in the traffic patterns, instead of recalculating the entire network. The existing program can only evaluate one alternative at a time.

2.2.7 Activity growth models

These models are very complex, with the detail involved in a single simulation run for one investment plan being very large. The two most significant studies which employ an activity shift or macro-economic model in conjunction with a transport model are the Northeast Corridor Study [22] and the Harvard-Brookings Study [1]. Lately, Robillard[23] has incorporated direct demand models to perform the modal distribution of network flows in the Harvard-Brookings model.

(3) Fundamental Concepts Used in the Network Evaluation Model

3.1 Overview, Assumptions and Simplifications

The purpose of this study is the development of a realistic, but easily used approach to the solution of the network evaluation problem. It must allow for separate cost-volume relationships for each link in the network, and for non-linear changes as development occurs. Contributions to network operation for unchanged links should be insertable into the analysis from either detailed link evaluation or approximation by the user.

The approach being utilized is deterministic. The highway network is assumed to consist of a series of nodes and connecting links. The nodes

represent cities, other major origin and destination points for the transport of people and commodities, or network branch points. Existing and projected demand between O-D pairs is given, stated in terms of volumes of vehicles of a given type or metric tons of commodities of a given category. Demand elasticity and the opportunity cost of cargo will also be associated with the O-D pairs vehicle combinations.

This study assumes that the traffic volumes in each link of the network are relatively low, sufficiently low that congestion costs, while considered in the consumer surplus, do not influence routing, determined by finding the minimum total cost path. Route splitting is not considered, not only to provide simplicity and efficiency in the evaluation process, avoiding iteration, but also because it was felt that congestion was not a significant factor in route choice in LDC's. For almost all O-D pairs, alternative routes with nearly similar costs usually do not exist. It is also assumed that user costs, at the screening stage, are largely insensitive to pavement condition and maintenance policy, i.e., to the difference between actual and approximated volumes.

Inflation, as a world problem, also impacts LDC's. But both the costs and benefits attributable to transport investments rise in consequence. Since the costs and benefits occur largely at different times, the ranking of investment alternatives might be sensitive to timing. This is less true if we assume a fairly constant stream of investments, and seek only a relative ranking. If the inflation rate is taken as a constant, and the distribution of pricing factors remains constant, the inflation rate may be viewed simply as a component of the discount rate, and constnat dollars may be used. These assumptions have been made.

3.2 Traffic Demand and Assignment

The traffic on the network originates from the supply nodes, its destination being the demand nodes. Transport demand is given in terms of origin-destination (O-D) pairs. A supply (origin) node represents a commodity source or production region, such as a port, an agricultural production, mineral resources, manufacturing area, etc.; whereas a demand (destination) node represents a city, town, etc., where the commodities are consumed. The annual base demand is determined by the model user, according to the population and its projected growth rate, the gross national income and its projected increase, future price of commodities, etc. Transport costs will then induce or reduce traffic around this base volume depending on supply-demand elasticity and the availability of transportation sources.

The model can handle up to seven different vehicle types, to be defined by the user. Typically, these will include passenger cars, buses, and a range of trucks or commercial vehicles. Within each vehicle category for one O-D pair, it is assumed that only commodities of similar time value of transport are carried. The number of substantially different commodity carrying vehicles is limited to five on the network. However, this should provide a broad enough spectrum for analyzing such aggregate types as fresh foods, grains, minerals, manufactured goods, etc.

Two options are available for the units in which transport demand is measured: number of vehicles per day for each vehicle category for each O-D pair; or number of cars and buses per day for each O-D pair and demand of commodities in metric tons per day for each commodity type and each O-D pair. From these volumes of commodities, the vehicle capacities, and the vehicle load factors, the required number of vehicles per day for each O-D

pair is easily computed.

Each vehicle will follow the sequence of links connecting the O-D pair which minimizes its total financial operating costs. These costs are determined from link operating speeds and conditions representing uncongested travel. No reassignment of the traffic is considered due to congestion, which does, however, effect transport costs, as described below. This limitation is not considered to be significant, since most of the links in LDC's are uncongested, and typically there is only one route connecting an O-D pair, which the vehicles must follow regardless of congestion effects.

The algorithm for minimum cost path traffic assignment is based on one published by Floyd[24]. The algorithm is applied for each vehicle type, determining its minimum cost route for each O-D pair. Initially, three NxN matrices are constructed, where N is the number of nodes in the network. The cost matrix, c, has as its elements the vehicle operating costs (financial) over each link, as defined by the two nodes at its ends. Infinite costs are specified if no link connects the two nodes. The time matrix, T, has as its elements the travel times on the links. The labelling matrix, L, has as its elements, in the initial stage, the row numbers of the matrix, i.e.,

$$L_{i,j} = i.$$

The logic of the algorithm proceeds by pivoting on every node of the network; i.e., it obliges all traffic to pass through this pivot node. It compares the resulting transport costs for each O-D pair (before and after the pivotting operation), saving the lesser cost. If the costs

after pivotting are the lesser, it updates the label matrix and the time matrix according to the new route. At the end of this pivotting process, the cost matrix C will contain the minimum transport operating costs for each O-D pair, the time matrix T will contain the resulting travel times, and the label matrix L the sequence of nodes to the destination node of the minimum cost route.

3.3 Consumer Surplus

In evaluating network alternatives, a measure of benefits must be introduced. These benefits are the savings in vehicle operating costs over the base network operating costs, for the base volume, plus the consumer surplus generated by induced traffic. These benefits are equal to the benefits accruing to the consumers and producers of the transported commodities, with the underlying assumption of indifference with respect to benefit distribution between consumer and producer. A proof of the above equivalence follows.

Assume that a commodity is produced at node A and consumed at node B. Then, supply-demand equilibrium establishes the unit price of the commodity at B as equal to the unit cost of production at A plus the unit transport cost between A and B (assumed to be invariant with respect to the volume transported). Similarly, after any improvements to the route between A and B, the new unit transport costs between A and B will equal the difference between the unit price of the commodity at B and the unit cost of production at A. Therefore, the change in unit transport costs between A and B, ($\Delta\theta$), is equal to the change in the unit cost of production at a, (ΔP_A), minus the change in the per unit price of the commodity at B, (ΔP_B):

$$\Delta\theta = \Delta P_A - \Delta P_B \tag{3-1}$$

The relationship between unit transport costs and the volume of commodity transported between A and B can be expressed in terms of the corresponding elasticity with respect to transport costs (θ) of demand:

$$T = A \cdot \theta^{e} \tag{3-2}$$

where T is the transport volume
A is a constant
θ is the unit transport cost
e is the elasticity

The total benefits to the economy may be expressed as:

$$Ben = \Delta\theta \cdot T + 1/2\ \Delta\theta \cdot \Delta T \tag{3-3}$$

where $\Delta\theta \cdot T$ measures the cost savings to the normal volume of traffic T

$1/2\ \theta \cdot \Delta T$ measures the benefits to the induced traffic, ΔT, attracted by the improved road

It may be proven that the computed benefits in (3-3) are the benefits of the consumers and producers of the regions served by the road. Figure 3.2 shows the corresponding supply and demand equilibria for the commodity in the two regions before and after the road improvement. The price in B falls by $-\Delta P_B$ and the price in A rises when the unit transport cost falls. At the same time the volume of traffic between regions in the traded commodity increases by ΔT. The increase in traffic is equal to the increased demand in B plus the decreased local supply there to the price drop. Also, for region A, it is equal to the increase in supply plus the decrease in local demand caused by the price increase. In region

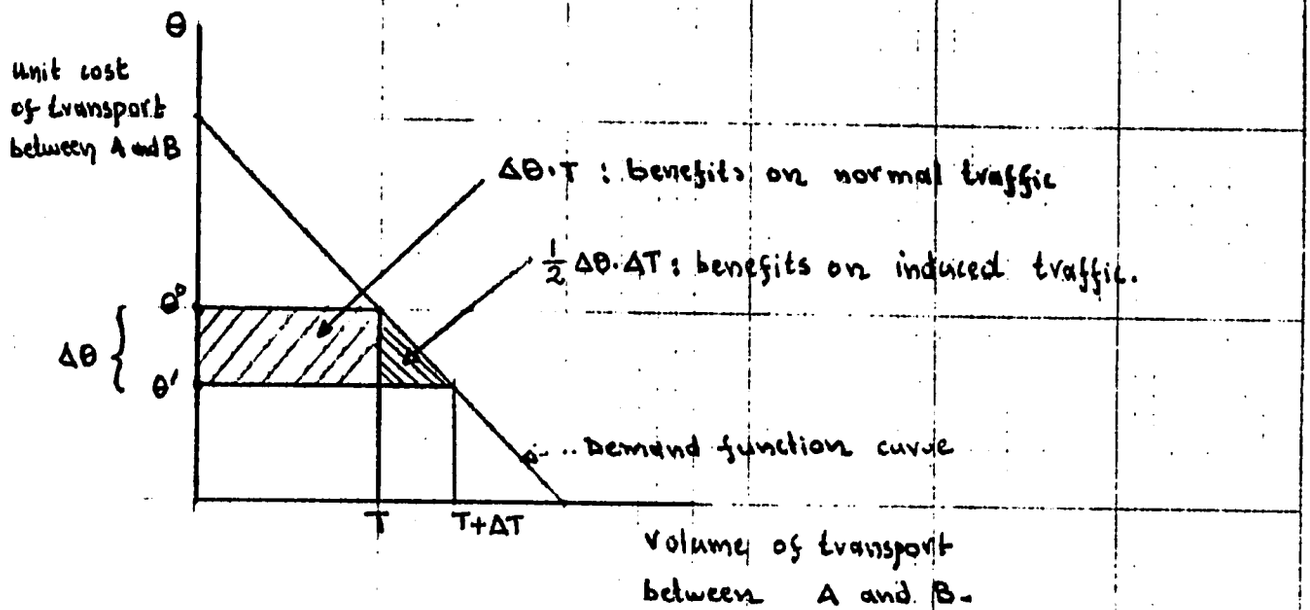


Fig. 3.1. Users' benefits calculation.

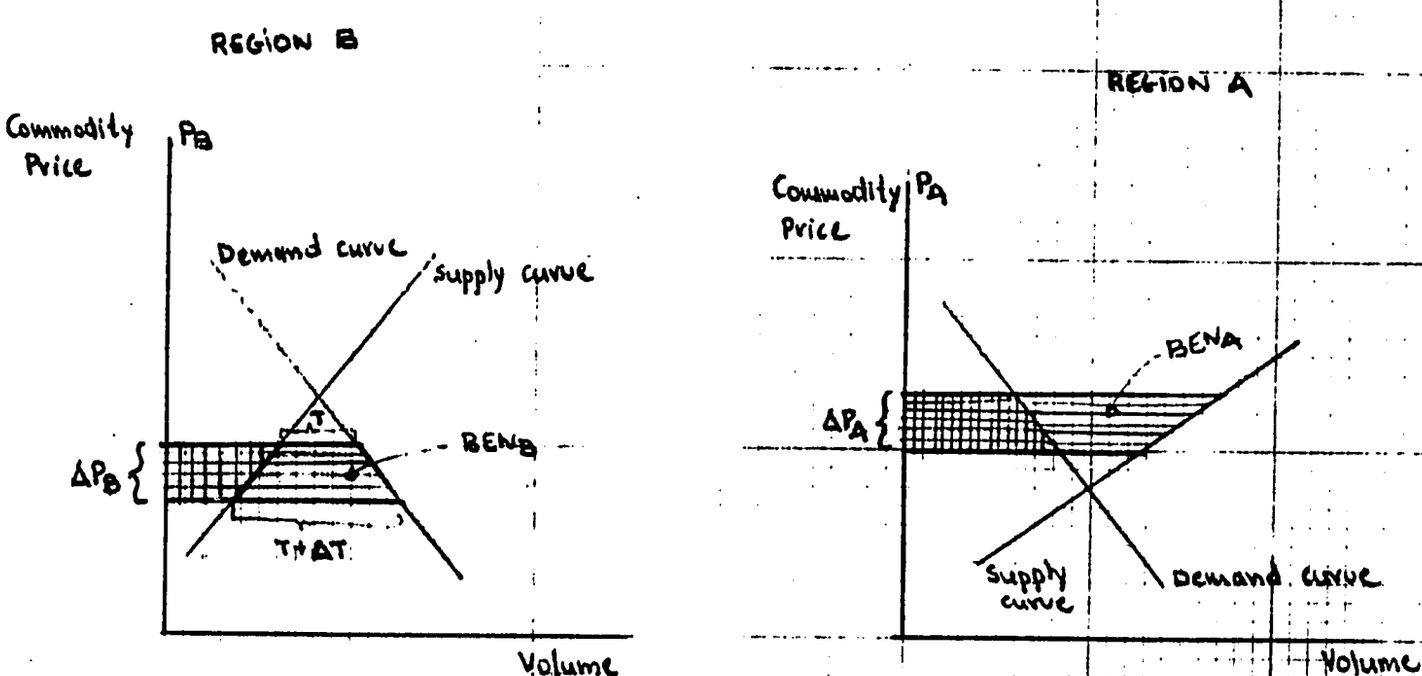


Fig. 3.2. Consumer surplus calculation.

B, the horizontally shaded area represents the total gain in consumers' surplus due to the reduction in the price of the commodity in B. The vertically shaded area represents the loss of local producers' surplus. This loss offsets a part of the total gain in the consumers' surplus, leaving an area measured by $-\Delta P_B\ (T + \frac{\Delta T}{2})$ as the residual gain to region B (Ben_B). Similarly, in region A, a part of the producers' surplus realized due to the price rise in A (vertically shaded area) is offset by the loss of local consumers' surplus (horizontally shaded area). The residual gain in A (Ben_A) is measured by $\Delta P_A\ (T + 1/2\ \Delta T)$. The total residual gain is thus:

$$Ben = (\Delta P_A - \Delta P_B)\ (T + 1/2\ \Delta T) = \Delta\theta\ (T + 1/2\ \Delta T)$$

These are the benefits observed when an existing route is improved. If A and B have no connecting route, then clearly demand does not exist for the commodity. However, a potential demand of T^0 units of commodity would exist if a route between A and B were built, where

$$T^0 = A(\theta^0)^e \quad ; \quad \theta^0 = P_B{}^0 - P_A{}^0 \tag{3-4}$$

and the analysis would proceed as before.

3.4 Congestion Effects

Transport costs on any link would increase if the link is congested. To evaluate congestion effects, the volume of traffic on the link is required, as is the capacity of the link. Since a mixture of vehicle types use the link, it is convenient to express all traffic in terms of

equivalent passenger car units (PCU) for the evaluation of congestion. This is done by multiplying the actual volumes of buses and trucks by their traffic equivalence factors (TEF). TEF is a function of the type of terrain (flat, rolling, or mountainous) and the average speed of the vehicles on the link, as determined by Roberts [1]:

$$TEF = 2+0.15\ (carspeed - truckspeed) \quad \text{for flat terrain} \tag{3-5}$$

$$TEF = 2+0.25\ (carspeed - truckspeed) \quad \text{for rolling terrain} \tag{3-6}$$

$$TEF = 2+0.45\ (carspeed - truckspeed) \quad \text{for mountainous terrain} \tag{3-7}$$

where carspeed is the average speed of a passenger car on the link

truckspeed is the average speed of the truck or bus for which TEF is being computed

The volume of PCU is then found by the sum of the equivalent traffic volumes over all vehicle types

$$PCU = \sum_{i=1}^{7} TEF_i \cdot VOL_i \tag{3-8}$$

Substituting into the binomial distribution

$$P[(\tfrac{y}{5} + .1) * capacity] = \frac{4!}{y!(4-y)!} RVOL^{y} (1-RVOL)^{4-y} \tag{3-10}$$

for y = 0 to 4, gives the part of each day for which a given volume is expected. For each of these volumes, a speed may be calculated as some loss over uncongested speed. The loss here is assumed to be

$$loss = 1 - (\frac{y}{5} + .1) \tag{3-11}$$

taken for an ideal or design speed (V), taken as 80 km/hr for level terrain, 65 km/hr for rolling terrain, and 50 km/hr for mountainous. Therefore

$$V' = V * loss = V\ [(1 - (\frac{y}{5} + .1)] \tag{3-12}$$

but not less than 0.1 V or greater than HCM calculated speed. Finally, average speed for a passenger car is computed by:

$$V_{AV} = \sum_{y=0}^{4} P[y] * PCU * V'/\ PCU \tag{3-13}$$

and velocity of other vehicles reduced by the same proportion. Congestion potential during some hours of the day may occur if the equivalent daily volume of traffic is greater than about 10% of the daily link capacity. Roberts [1] developed an approximation to represent the variation of traffic during an average day, sensitive to the stronger peaking noted for more heavily traveled roads. This avoids the need to specify, for each link, its distribution of daily traffic.

Roberts represented the probability distribution of the level of traffic as a probability mass function of the link capacity. He uses a binomial distribution, of order 4, to represent the probability of the occurrence of volume during the day within each 20% intervals of capacity. He takes the probable volume to be

$$RVOL = 1.25\ (\frac{PCU}{CAP} - .10) \tag{3-9}$$

where PCU = equivalent vehicles per day/16
CAP = hourly roadway capacity in PC Units

(4) A Network Strategy Evaluation in Scheme

4.1 Overview

The network evaluation model generates, screens, and evaluates network development strategies for low volume road networks. Given present road network demand on an origin-destination basis, potential demand if road service were provided, demand elasticity, and data on the cost potential network investments, the model generates sequences of link investments, screens them for overall value and satisfaction of the economic constraints, and performs cost-benefit analysis of the most promising strategies. The model is integrated with the Highway Cost Model, which simulates investment strategies of single links. The model may deal with each individual link with the accuracy of the HCM or use user-supplied cost-benefit estimates, producing a ranked list of network strategies, with their evaluations and the timings of each included link investment.

The model consists of four computer programs and their data files, which store network configuration and strategy data, linksstrategy data, and origin-destination demand data. The programs are an input data processor, the HCM, a network strategy generator, and a network strategy evaluator which simulates the operation of the network over the analysis period. The model simulates the construction and maintenance activities of each link, along with user operating costs, using costs developed by the HCM or elsewhere, segregated by local and foreign financial cost components. Simulation and evaluation of the network operation includes the routing of traffic, based on vehicle operating costs, using an all-or-nothing minimum cost path criterion. The system is data base oriented, with the general flow

of information in the model shown in Figure 4-1. A user may exercise any part of the model as long as information needed for that part has been developed previously.

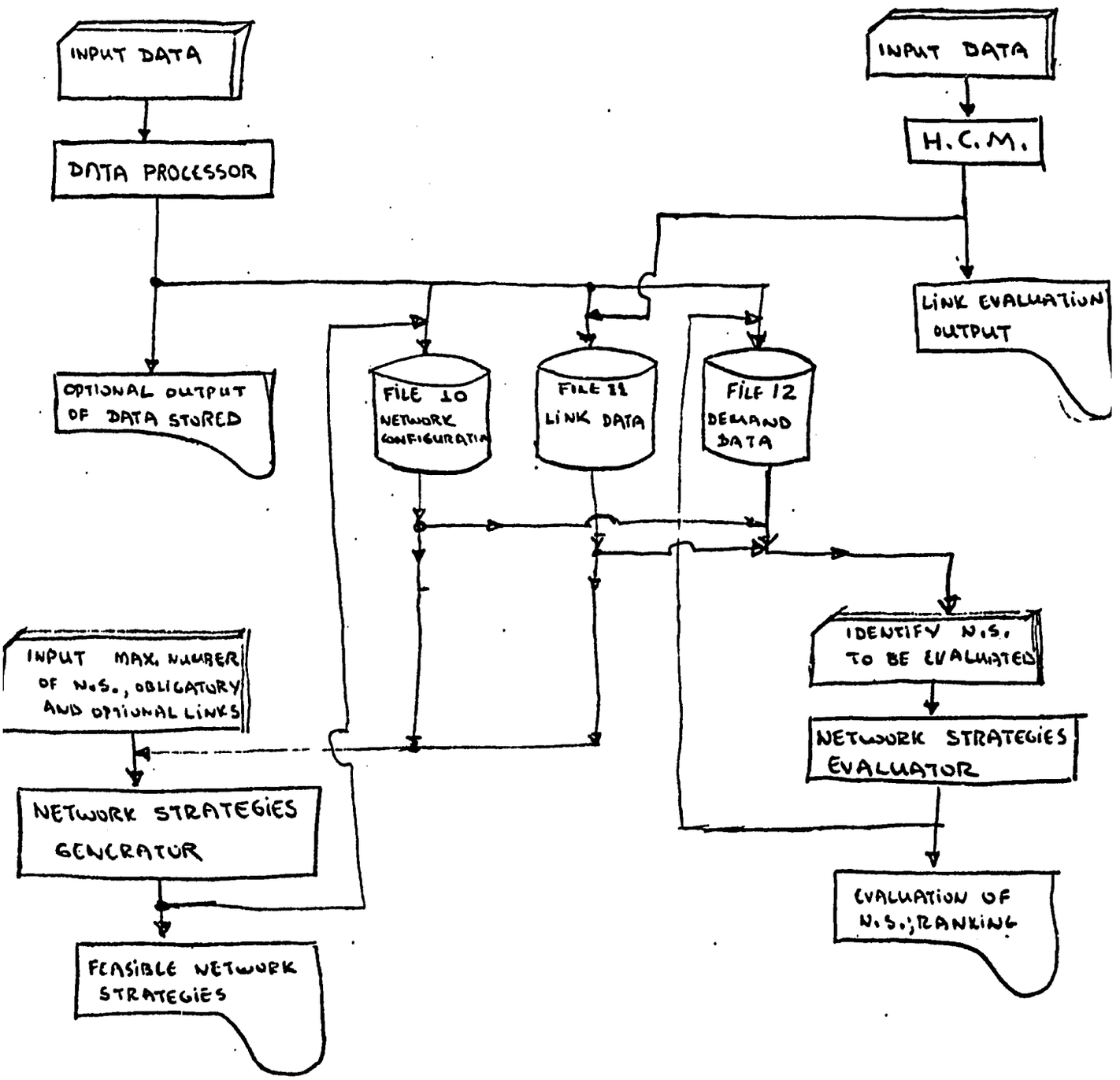
The generation and screening of network strategies are based upon two types of constraints: Limits on the timing of link investments, the amount by which a link strategy may slip in time from its initial sequencing within the HCM; and capacity limits for constructing and maintaining the network. Initially, financial and skilled labor constraints by regions of the network were included. To limit the choice among the large number of remaining potential combinations of link strategies, the model allows the analyst to assign a value, a social criticality index, to the inclusion of any link strategy within the network. Further pruning among feasible network strategies is then based upon maximizing the cumulative social criticality index for all included strategies. A small number of network strategies are kept, to be evaluated at the analysts's request, and ranked after evaluation.

4.2 Constraints

A network strategy is an initial configuration of the network plus a sequence of changes, by construction or changed maintenance policies, to some of the network links over time. It is a combination of a base network plus a choice among some alternative link improvement strategies. The feasibility of a network improvement strategy is based on whether it satisfies constraints introduced to prune the list of generated network strategies. Assuming an annual budget is allocated for highway construction and maintenance from the national budget, those funds will be distributed to various regions of the country, depending on their various economic,

Figure 4.1.

NETWORK SIMULATION SYSTEM FLOW



social, and political needs. Therefore, each feasible network strategy will have annual costs of construction and maintenance activities not higher than the allocated annual regional budget. There are two additional economic constraints typical of LDC's; limited foreign exchange and skilled labor supply. Since most of the money available for initial construction comes from abroad, either as aid or low-interest, long-term loans, the balance of payments usually constrains the growth of the country. Therefore, the model has been designed to screen potential feasible network strategies for limitations on available regional foreign exchange. Similarly, skilled labor availability may constrain the set of feasible alternatives.

Each network strategy which satisfies the above constraints is feasible. Since the feasible network strategies may be numerous, and some links might be desirable for non-economic reasons, the model allows the analyst to assign a value, the social criticality index, to force or promote the inclusion of a link strategy with the network. These criticality indices are arbitrary numbers, reflecting the analyst's initial ranking of link improvements; they may reflect factors such as national unity and defense, penetration to potential resources or agriculture, scenic highways, or political influences, as well as other factors.

4.3 Link Evaluation

Each link is simulated by the HCM over the evaluation time horizon, computing construction and maintenance financial and economic costs, and the total expenditures for the link for each year of the analysis period for each of its alternative strategies. In addition, the HCM simulates the vehicle operating costs on the link according to road conditions, and approximate traffic volumes, but ignoring vehicle interaction effects

(congestion). The network simulation model takes this information about the vehicle operating costs, and simulates the vehicle operation according to the traffic calculated to be on the link from the entire network. Any delays due to possible congestion are computed, and the total transport costs for each O-D pair can then reflect these time-loss costs for each link.

A link strategy is a time sequence of improvements on a link. A link is composed of a series of segments, each of which may have different pavement design, surface type, alignment, grade, etc. Improvements are projects, related to the segments, and consist of upgrading or changing the riding surface, altering maintenance policies, etc., which may be programmed for specific years. The HCM then simulates the various activities of the sequence of improvements, computing the resulting construction, maintenance and vehicle operating costs on the link over time.

The HCM requires a significant level of detailed information about a network link. If a link is under consideration for development or upgrading, this data is probably available. But for otherlinks, it may not be, or its collection not worthwhile due to the low significance of the link. Similarly, in very preliminary studies, a planner may not wish to utilize the accuracy of the HCM because of the data gathering burden. For those reasons, this model allows the user to by-pass the HCM for any network link and specify directly public costs and operating characteristics, year by year, for any link.

4.4 Network Strategy Generation and Screening

The purpose of a network strategy is to specify a feasible program of network improvements over time. To be feasible, it must satisfy the regional financial budget, foreign exchange, and skilled labor constraints

in each year of the analysis period. The network strategies are generated from an existing or potential network configuration and links and link strategies introduced by the decision maker. The network consists of three types of links: existing links for which no change is planned; links for which change is planned and one of the changes strategies must be included, (obligatory links); and links for which change is optional, to be included if possible within the constraints, (optional links). Obviously, only one strategy per link may be included in the network strategy.

The generation of network strategies is coordinated with a branch and bound technique, comparing resultant incurred costs, for adding a link strategy to the fixed constraints. The inherently large calculation requirements for a tree search is cut-off at the bounds of a feasible solution. To limit the number of alternatives presented to a planner the set of feasible solutions is pruned to a "promising" set using the social criticality index. A single "best" solution is not sought, since realistic criteria are not available or exact.

Unchanged links need not be considered in strategy generation. Neither do obligatory links with only one strategy, which is fixed in its timing. This forms the base network; its costs may be subtracted from the constraints. Then link strategies are introduced to the network sequenced according to the highest outstanding social criticality index, until the constraints block the addition of new link strategies or there are no more links to add. Strategies from the remaining obligatory links are added first, then for optional links. If the generation is blocked prior to inclusion of the obligatory links, the solution is not saved. Additional solutions are then generated by skipping the timing of some strategies in order to add

more links into the network strategy. Next, alternative strategies are substituted, also searching for the ability to include additional links to raise the cumulative criticality index. Finally, some optional links are dropped to test for the existance of better solutions with other configurations.

This process creates a large number of feasible solutions. For the evaluation process, however, the user wishes to work with a limited number of "promising" strategies. Therefore, the generation process retains only N promising solutions, those with the highest cumulative CI, where N is set by the user.

4.5 Network Strategy Evaluation

4.5.1 The Base Network

The base network establishes a basis for evaluation of alternative network strategies, the base from which incremental costs and traffic volumes are measured. The base network consists of the network existing at the beginning of the time horizon, plus the fixed development plans as represented by obligatory, single strategy links specified without slippage by the highway planners. The base network is simulated at the same level of detail as any other network proposed as a network strategy.

4.5.2 Traffic Demand Adjustments

In all networks, including the base network, the demand between O-D pairs may also change over the years. This is a result of the traffic demand function:

$$T = A \cdot \theta^{e} \qquad (4\text{-}1)$$

If θ, the transport costs, changes, T will also change, since the traffic demand is sensitive to transport price changes if the price elasticity e is non-zero. The new traffic demand is:

$$T' = A \cdot (\theta')^e = T \cdot \left(\frac{\theta'}{\theta}\right)^e \tag{4-2}$$

Also costs may increase if congestion occurs, determined by the traffic demand and the capacity on each link.

4.5.3 Evaluation of Benefits

The simulation of each network consists of a process to determine cost and volume of transport between each O-D pair for each vehicle type and each analysis year. This simulation is performed using the following steps:

1. A minimum cost route is found for each O-D demand pair. Unit opportunity costs and transit times are found.
2. The traffic volume on each link is calculated from the routing of all O-D pairs. Then congestion delays are calculated for all links.
3. For each O-D pair, congestion delays,are added to the transit times. With this total transport cost, operating plus cargo opportunity cost, the demand is adjusted to reflect induced demand over that of the base network. If no route exists in the base network for a demand, then the base transport cost is an input variable reflecting the maximum transport cost feasible to a producer for any sales.

The evaluation process consists, quite simply, of calculating the consumer surplus for each O-D pair and adding them together for each year.

Given the costs and volumes for both the base network and the alternative, equation 3-3 may easily be applied in the form

$$CS = 1/2\ (\theta - \theta')\ (T + T')$$

where θ, T are cost and volume for the base network
θ', T' are those for the alternative

Similarly, economic costs for construction and maintenance may be calculated for each link and added for each year. The difference between the total CS for all O-D pairs and the costs for all links is the net benefit for the year. The benefits for all years may be combined by discounting them to the present to yield a single value measure, the NPV (net present value) resulting from the incremental investment over that of the base network. Alternative strategies can similarly be ranked by the magnitude of this value.

The choice of NPV as a value measure instead of other alternative measures, such as cost/benefit ratio, is based on the assumptions in the model that the process is capital limited. All strategies will attempt to utilize as completely as possible the budget available up to the constraints. Therefore, the costs for all alternatives will be nearly equal.

(5) Conclusions

5.1 Results

A preliminary computer version of this model is now in its final state of checkout. It appears to operate effectively for up to 30 alternative link strategies on two to ten links with alternatives. Input to all processors in the system is by means of Problem Oriented Language in order to make it easy to use. A user's manual will be produced shortly.

A case study to test this system is also in preparation. The network around the Asela-Dodola project in Ethiopia has been chosen because of its relatively easy separability from the large network and the expected diversion of traffic that the project will stimulate.

One problem which this model will create for planners is its reliance on O-D demand data. In most LDC's this form of demand data is less well defined than the link traffic data. It is the data used only in gross planning and not collected for the more detailed usage implied here.

5.2 Future Work

Obviously, more experience must be sought with this model to perform a significant evaluation of its utility. Beyond that areas for significant improvement can readily be identified. These can be subdivided into three types: accuracy improvements, generalizing applicability, and extending the methodology.

Accuracy improvements currently envisioned include:

1. Treatment of backhaul traffic
2. Update of maintenance costs to reflect actual traffic
3. Update user costs to reflect consequences of maintenance

Applicability can be extended by broadening the treatment of constraints to allow for national bounds in conjunction with region limits. More types of constraints are also foreseen. Lastly, the model could be extended in two ways: first by developing a cost generator somewhat more crude than HCM to provide easier generation of link data, and second by treating costs and demand more on a stochastic basis. The first is considered of higher priority, and will be pursued first.

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APPENDIX A

Agreement Between

The Massachusetts Institute of Technology

and

The Ethiopian Highway Authority

Room 1-171

January 27, 1975

General Manager
Ethiopian Highway Authority
Addis Ababa, Ethiopia

Dear Sir:

This letter will confirm the details for a joint program in highway planning which were discussed between you and members of my staff during 8-14 January, 1975. It describes the goals and scope of the study, and addresses scheduling, staffing and funding issues.

The goal of the program will be to improve the project evaluation and selection methods of the Ethiopian Highway Authority (EHA). The effort will be a cooperative one, and it is understood that the successful outcome of the program will be the joint responsibility of the EHA and the Massachusetts Institute of Technology (MIT).

The first phase of the program will be to improve methods of project evaluation used by the EHA. Consideration will be given to major policy issues of project evaluation, including the standard and timing of construction, and possibilities for staging construction.

The second phase of the program will be to improve methods of program planning for the highway network as a whole. Emphasis will be placed on identifying methods for choosing among projects, given development goals and priorities, and resource and budget constraints.

An optional third phase of the program will focus on programming and budgeting issues. The objective here will be to integrate planning decisions with program and budget considerations.

The three phases of the work will emphasize analytic methods, and the training of EHA personnel in their use and applicability. An important part of the work will be to demonstrate both the advantages and limitations of the various approaches to project evaluation and selection, and to put them in a coherent framework for use by the EHA.

The first phase of the work program--to improve methods of project evaluation--will include the following: demonstration

of an analystic model which has been developed at MIT for use in project evaluation (the Highway Cost Model); education of a member of the EHA staff at MIT in project evaluation methods and in the use of the model; and development of a project evaluation manual.

During their recent trip, members of my staff and the EHA jointly identified several projects for which feasibility studies have recently been completed, and which illustrate the range of project types for which the EHA has responsibility. These projects will be turned into case studies to demonstrate the use of the model and to provide a basis for a critical review of EHA evaluation procedures. This work will be performed in the United States during the period January to June 1975.

During this same period, a member of the EHA staff will come to the United States and serve as a Fellow at MIT's Center for Advanced Engineering Studies. In addition to course work in the area of project evaluation, he will work closely with my project staff on the case studies and on the development of a project evaluation manual. He will be sufficiently familiarized with the operation of the model so that he can coordinate use of the model by the EHA, and supervise modifications to the model and its data base as additional data becomes available from current and future studies.

Members of the MIT project staff will come to Ethiopia to present the results of these efforts to the EHA in July or August of 1975. During this period, they will also attempt to install the Highway Cost Model on the EHA's new Burroughs computer. It is therefore advisable that the date of the trip be kept flexible so that we can ensure that the computer has been delivered and is running. At the latest, however, my staff must return to Boston in early September, 1975 to prepare for the academic year.

It must be understood that the Burroughs machine is somewhat small in relation to the MIT program, but that it may nevertheless be possible to install the Highway Cost Model because of certain features of the Burroughs equipment. Efforts will be made in the U.S. prior to arrival to facilitate conversion; however, should the conversion be either too time-consuming or impossible, the EHA will have to make other arrangements to use the program.

If installation of the program is successful, a parallel feasibility study will be undertaken in Ethiopia. The Planning & Projects Branch of the Planning and Programming Division will

prepare a conventional feasibility study, while the EHA staff member, with the assistance of my project staff, will prepare a feasibility report on the same project using the Highway Cost Model.

The second phase of the work program--to improve methods of project selection--will proceed as follows: In either August of 1975 or February of 1976, a second member of the EHA staff will come to MIT as a Fellow of the Center for Advanced Engineering Studies to undertake work in methods of project selection. While he will be familiarized with the results of the first part of the work program, primary emphasis will be placed on course work in planning, programming, and budgeting. As with his predecessor in the program, he will work closely with members of the MIT faculty in developing new methods of program planning for the road network as a whole. During this phase of the work, MIT will rely heavily on the EHA to identify development objectives, and the nature of the resource and budget constraints which should be considered in the work.

Upon completing approximately five months of study at MIT, the EHA staff member will return to Ethiopia to reassume his duties in the Planning and Programming Division.

During June of 1976, I and my staff will come to Ethiopia to assist you in preparing an evaluation of our cooperative effort. If it is agreed that this program has been successful and mutually beneficial, and if the necessary approvals can be obtained, the period of this agreement will be extended.

This optional third phase of the program will focus on programming and budgeting methods. Depending upon the success of our previous efforts and the availability of funding, this phase of the work may include provision for a third member of the EHA staff to come to MIT to take courses, to work with our faculty, and to undertake studies of specific interest to the EHA.

MIT, as part of its contract with USAID, will cover all of the following costs: salaries of MIT staff, travel of MIT staff to and from Ethiopia, and living expenses of the MIT staff while in Ethiopia. In addition, MIT will provide office space and secretarial assistance to members of the EHA staff sent to MIT during the period of this arrangement.

EHA will be responsible for the following costs: salaries of EHA staff assigned to the program either in Ethiopia or in the United States. In addition, the EHA will provide office

space and secretarial assistance to MIT project staff during their periods of work in Ethiopia.

As of this date, the question of responsibility for tuition and living expenses of EHA personnel who come to MIT has not been settled. MIT has been authorized by AID to use current contract funds to pay for the first participant, but no additional funds have been allocated to the project, nor has any provision been made to cover the costs of future participants. However, this should not delay our program, and I am confident that a source of funds can be found. A summary breakdown of the costs involved is attached.

Both the EHA and MIT will provide any letters required by the other to assist in the fulfillment of visa requirements.

As principal investigator under the USAID Funding Agreement, I will serve as the program coordinator for MIT; the Chief of the Planning and Programming Division will serve as coordinator for the EHA. In addition, both MIT and EHA will designate at least two individuals to participate in the exchanges described above. Each will insure that the exchange participants are properly qualified in either engineering or economics so that they may undertake the tasks alloted to them.

I trust that the above meets with your approval and I look forward to allong period of fruitful cooperation.

Very sincerely,

Fred Moavenzadeh
Professor of Civil Engineering

cc. Dr. Withers
John Fry
Professor R.S. Eagleson

APPENDIX B

A WORKSHOP ON HIGHWAY PLANNING AND PROJECT EVALUATION

Sponsored by

The Ethiopian Highway Authority

and

The Massachusetts Institute of Technology

To be Held in Addis Ababa, Ethiopia

September 1-3, 1975

PURPOSE AND OBJECTIVE:

The purpose of this workshop is to bring together a group of East African Highway Officials for discussion and review of current methodologies available for project evaluations in less developed countries. The program will focus on highway project evaluation, and will present the results of a study currently being sponsored by the AID's Office of Science and Technology in Highway Transportation Planning in Developing Countries.

In addition, the issues of employment and the opportunities available for it in the highway planning stage will be discussed.

The workshop uses the results of case studies that have been carried out on East African Highway Projects to demonstrate the technical issues important in Highway Planning.

The workshop is sponsored jointly by the Ethiopian Highway Authority, Massachusetts Institute of Technology, and the Agency for International Development.

Additional information can be obtained through:

Ato Hailu Shawel
General Manager
Ethiopian Highway Authority
PO Box 1770
Addis Ababa, ETHIOPIA

Mr. John Fry
Agency for International Development
New State Department Building
Washington, D.C. 20523

Fred Moavenzadeh
Room 1-171
Department of Civil Engineering
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Designation of speakers and panel members is tentative.

PROGRAM

Monday, September 1

Registration (9:00 - 10:00 AM)

Session I (10:00 - 12:00 Noon)

Introductory remarks:

Speakers: Ato Hailu Shawel, Ethiopian Highway Authority (EHA)
Professor Fred Moavenzadeh, MIT
Dr. John Withers, AID or The Honorable Arthur W. Hummel, U.S. Ambassador to Ethiopia

Session II (2:00 - 5:00 PM)

Project Evaluation Methodologies

Speaker: Richard Eckaus, Professor of Economics, MIT

Panel: Ethiopian Planning Commission
ILO (Dr. Ajit Bhalla)
EHA (Ato Yusuf)
AID (Mr. John Fry)

Tuesday, September 2

Session III (9:00 - 12:00 Noon)

Highway Design Standards

Speaker: Clell G. Harral, IBRD

Panel EHA (Mr. Truneh, Mr. Moges)
Representative from an international consulting firm
TRRL (Mr. Hide, British Transport and Road Research Laboratory)
MIT (Mr. Fred Moavenzadeh)

Session IV (2:00 - 5:00 PM)

Highway Design Standards: Field Work and Case Studies

Speaker: Richard Robinson, TRRL

Speaker: Robert Wyatt, MIT

Panel: IBRD (Dr. Agarwal)
EHA (Mr. Abera)
AID (Mr. Stearns)

Wednesday, September 3

Session V (9:00 - 12:00 Noon)

Labor-Capital Substitution in Highway Construction - Major Issues:

Speaker: Dr. Ajit Bhalla, ILO

Panel: IBRD (Dr. Harral)
EHA (Ato Yusuf, Ato Teshome Workie)
SEDA (Swedish Economic Development Agency)

Session VI (2:00 - 5:00 PM)

Labor Capital Substitution in Highway Construction - Case Studies

Speaker: Janet Rossow, MIT

Panel: ILO (Dr. Bhalla)
IBRD (Dr. Agarwal)
AID
EHA

INTERNATIONAL AGENCIES INVITED TO PARTICIPATE

Agency for International Development (AID)
Washington, D.C.

Canadian Economic Development Agency (CEDA)
Ottawa, Canada

Economic Commission for Africa (ECA)
Addis Ababa, Ethiopia

International Bank for Reconstruction and Development (IBRD)
Washington, D.C.

International Labour Office (ILO)
Geneva, Switzerland

International Road Federation (IRF)
Washington, D.C.

International Road Transport Union (IRT)
Geneva, Switzerland

Laboratoire Central des Ponts et Chaussees
Paris, France

Overseas Development Agency (ODA)
London, England

Permanent International Association of Road Congresses (PIARC)
Paris, France

Societe Anonyme D'Economie Mixte Au Capital (BCOM)
Paris, France

Swedish Economic Development Agency (SEDA)
Stockholm, Sweden

Transportation and Road Research Laboratory (TRRL)
Crowthorne, England

United Nations Industrial Development Organization (UNIDO)
Vienna, Austria

HIGHWAY DEPARTMENTS INVITED TO PARTICIPATE

1. Kenya
2. Zambia
3. Sudan
4. Somali
5. Malawi
6. Mozambique
7. Tanzania
8. Uganda

APPENDIX C

List of Participants

List of Participants

Dr. Fred Moavenzadeh -- Principal Investigator

Dr. Paul O. Roberts -- Co-investigator

Dr. Robert Logcher -- Co-investigator

Robert Wyatt -- Project Manager

Brian Bradmeyer -- Research Engineer

Fredric Berger -- Research Assistant/Graduate Student

Dimitrios Tsamboulas -- Research Assistant/Graduate Student

Sam Dzirasa -- Research Assistant/Graduate Student

Anil Bhandari* -- Graduate Student, Tanzanian National

Aberra Wolde-Sadik -- Fellow, Center for Advanced Engineering Study, Ethiopian National

Zemen Lebne-Dengel* -- Graduate Student, Ethiopian National

Johndell Brown* -- Undergraduate

Gary Fostel -- Undergraduate/Programmer

Daniel Franklin -- Undergraduate/Programmer

Margaret Scott Gaines -- Administrative Assistant

Barbara Middleton -- Project Secretary

* Not paid out of Project Funding.

APPENDIX D

List of Contacts

Ethiopia

Ethiopian Highway Authority (EHA)

Hailu Shawel -- General Manager

Yusuf Ahmed -- Planning and Programming Division, Manager

Jack Gunther -- Supply and Equipment Manager

Ato Kasahoun -- Planning and Programming Division Staff

Ato Mengiste -- Planning and Programming Division Staff

Ato Woldu -- Project Superintendent

Ato Shifferaw -- District Manager

Aberra Wolde-Sadik -- Planning and Programming Division Staff

Adella Lulseged -- Head, Contract Construction Division

Haile Selassie Mengistu -- Head, Design Division

Nick Ortega -- Head, Survey and Photogrametry

Ato Asfaw -- Head, Photogrametry Section

United States Agency for International Development (USAID)

Dr. John Withers -- Director of Mission

Burton Gould -- Deputy Mission Director

Roderick MacDonald -- Engineering Advisor

United States Embassy

Mr. Wyman -- Deputy Chief of Mission

Others

Mr. Rebbi -- Systems Representative, IBM World Trade Corporation

G.B. Sooden -- Manager, Burroughs Machines Limited

David Bangert -- Resident Engineer, and Ato Testa -- Contract Superintendent, De Leuw Cather International Incorporated

Ethiopia (continued)

Robert Burns -- Harvard Institute for International Development

A.Z. Garoufalias -- Administrative Manager, Zorzi Giuseppe Construction Company

Kenya

Ministry of Works

F. E. Nderito -- Assistant to Chief of Roads

N. P. Radier -- Chief Engineer of Roads

G. Wabuke -- Chief Development Engineer, Roads Division

Basil Coukis -- Chief Advisor of Roads

Regional Economic Development Services Office (REDSO)

Edward Hogan -- Director

Robert Fedel -- Deputy Director/Chief Engineer

Albert Karian -- General Engineering Advisor, East African Region

David Gephart -- General Engineering Officer/Division Chief

John Westly -- Economics Advisor/Division Chief

United States Agency for International Development (USAID)

Charles Nelson -- Director of Mission

Lois Richards -- Program Officer

International Bank for Reconstruction and Development ((BRD)

Stanley Hayden -- Head, Transport Branch

Jacques Yenny -- Economist, Transport Branch

Others

Mr. Bodsworth -- International Computers Limited

Mr. Rostrut -- IBM World Trade Corporation

Professor A. J. Francis -- University of Nairobi

H. J. Mylchrest -- Senior Consultant, Inbucon

Tanzania

Ministry of Communications and Works

Ken Jardine -- Technical Assistant/Planning Department

Regional Economic Development Services Office (REDSO)

Pushkar Brahmbhatt -- Civil Engineer

United States Agency for International Development (USAID)

Werner Johnson -- Director of Mission

Others

M. Merritt -- International Computers Limited

United Kingdom

Transportation and Road Research Laboratory (TRRL)

Dr. Eric Tingle -- Head, Overseas Unit

P. Boffinger

Henry Hide

John Rawlt

Dick Robinson