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A METHODOLOGY FOR INTERCITY TRANSPORTATION PLANNING IN EGYPT

by

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PREFACE

This report is one of a series of publications which describe various studies undertaken under the sponsorship of the Technology Adaptation Program at the Massachusetts Institute of Technology.

The United States Department of State, through the Agency for International Development, awarded the Massachusetts Institute of Technology a contract to provide support at M.I.T. for the development, in conjunction with institutions in selected developing countries, of capabilities useful in the adaptation of technologies and problem-solving techniques to the needs of those countries. This particular study describes research conducted in conjunction with Cairo University, Cairo, Egypt.

In the process of making the TAP supported study, some insight has been gained into how appropriate technologies can be identified and adapted to the needs of developing countries per se, and it is expected that the recommendations developed will serve as a guide to other developing countries for the solution of similar problems which may be encountered there.

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ABSTRACT

This paper describes the development of the Egypt Intercity Transportation Model, designed to assess alternative transportation investment, maintenance, operating and pricing policies within Egypt. The Intercity Model encompasses movements of both intercity freight and intercity passengers on highway, railway, and waterways, and predicts transportation system performance, costs, and impacts resulting from different policies that may be specified. The Model incorporates a number of state-of-the-art analytical procedures and features particularly suited to analyzing transportation problems in developing countries, including:

1. An equilibration procedure which provides a simultaneous solution of the generation, distribution, modal split and assignment problems;
2. Interactions among investment, maintenance, operating and pricing policies through the use of simulation models (rather than closed-form functions) to estimate link costs; and
3. Explicit treatment of constraints on availability of transportation services -- not only link capacity (congestion), but also fleet capacity and the potential inability of modes to satisfy all of the latent demand.

INTRODUCTION

The Government of Egypt, through its Ministry of Transport and Transportation Planning Authority, has been engaged in a comprehensive effort to overhaul its transportation infrastructure and to strengthen Egyptian institutional capabilities in investment planning and evaluation, and in formulation of effective maintenance, operating and pricing policies. In parallel with this thrust, we have conducted this research project through Cairo University and the Massachusetts Institute of Technology under the joint Technological Planning Program with the cooperation of the Egyptian Transport Planning Authority.

The objective of this study has been to develop analytical methods to assess alternative transport investment, maintenance, operating and pricing policies within Egypt. This has entailed designing and building a computerized model to predict transportation system performance, costs, and impacts as functions of selected transportation policies. The scope of this project has encompassed both passenger and freight movements on the highway, railway and inland waterways modes.

The model we have developed is referred to as the Egyptian Intercity Transportation Planning Model, or more simply the Intercity Model. The completion of this Model has entailed several interrelated areas of investigation in engineering, economics and operations research, including:

1. A review of policies affecting intercity transportation and identification of those that could be feasibly represented within a transportation model;

2. For those policies selected above, specification of exactly in what ways the policies affect transportation performance and costs through cause-and-effect relationships (e.g., improvements in system reliability through investments in new construction, new technology, or maintenance; changes in user-perceived costs due to tariff revisions or to improvements in system reliability);

3. Design and development of analytical models to capture policy-sensitive shifts in intercity travel demand, modal choice, system performance, and costs on the highway, rail and waterways networks;

4. Definition of indices to evaluate the impacts of different policies on owners, operators, and users of the system within each mode; and

5. Assessment of data requirements, collection of data, and calibration of models to the current Egyptian situation.

In describing Model development, this paper focuses particularly upon the analytical component of the project (item 3 above). Section 1 gives an overview of the Intercity Model, identifying its components, describing its basic operation, and isolating those features which have been included to meet the special transport circumstances that exist in Third-World countries such as Egypt. Section 2 considers relationships describing demand for transportation among both passengers and freight, and the interaction between the volume of demand and the level of service and cost of transport provided. Section 3 discusses the estimation of cost and performance measures representing the supply of transportation services. Simulation models are employed in lieu of

closed-form link cost functions; the viewpoints of transport owners and operators, in addition to users, are explicitly taken into account. Section 4 presents the equilibration between demand and supply, stressing simultaneous solution of the trip generation, trip distribution, modal split, and assignment problems. Section 5 concludes the paper, giving examples of case studies to be investigated in Egypt.

1. OVERVIEW OF MODEL STRUCTURE

(a) Transportation Equilibrium

Analysis of transportation policy within the Intercity Model takes place within an equilibration process. On one side of the equilibrium are those factors affecting transportation demand --i.e., factors influencing the need or propensity to travel, the types and numbers (or quantities) of people and goods desiring to travel, the geographic locations at which demand for travel arises, and the characteristics of individual travelers or goods determining preferred modes of travel. On the other side are those factors affecting transportation supply --i.e., factors determining the kinds of transport servicing different passengers or commodities, the levels of service provided, the costs seen by users for various levels of service and resource consumption, and associated costs seen by owners and operators of the system.

Transportation Demand

It is widely recognized that the demand for transportation is not a direct demand but rather a derived one. Transportation demand arises through a combination of spatial, physical, economic and social factors leading, for example, to non-homogeneity in the distribution of resources, specialization of production, comparative advantages, or any combination of these.

Although macro-economic predictions are not included within the Intercity Model, shifts in demand (which can be specified exogenously) would result from actions such as the following:

1. Structural changes or growth in various sectors of the economy: e.g., creation of new industrial or manufacturing plants, development of natural resources, shifts in food, fodder or cash crops grown,

investment programs in housing or public or private facilities, opening of new areas for tourism, changes in defense needs;

2. Encouragement of, or responses to, changes in production and consumption of goods: e.g., adjustments in regulation of imports or exports, changes in diet or personal consumption habits, technological innovation in industry, shortages of scarce commodities (forcing reductions in demand or diversion to substitutes), changes in price of raw materials or finished goods;

3. Changes in the geographic dispersion of people and goods: opening of new areas for development, construction of satellite cities, increased urbanization of areas surrounding Cairo and other major cities;

4. Changes in the social fabric of Egypt: e.g., programs to control rates of population growth, shifts in the structure, composition, and demographic characteristics of families, imposition of income redistribution schemes and ignition of rising expectations among the general population.

Transportation Supply

Supply of transportation services arises through the allocation of resources and regulation of operations and prices by owners of transport links and operators of transport fleets throughout the network. The transport industry in Egypt comprises many individual owners and operators (both public and private), and the net level of service perceived by users is the result of interactions among all actors in the network: e.g., the interaction of highway owners (the Government) and trucking operators (public or private companies) to make available truck freight service to users; interferences among many operators on an

owner's link (congestion); and competition for scarce fleet capacity among potential users (crowding; foreclosure of modal choice).

To enable one to calculate the equilibrium between transport demand and supply, those aspects of system performance (supply) relevant to user choice* of transportation services (demand) are typically reduced to actual or equivalent monetary costs. Individual cost terms (e.g., fare or tariff; travel time costs; perceived costs attributable to loss or damage, reliability of travel time, and so forth) are then assembled within a Generalized Cost Function which forms the basis for calculating equilibrium.

In past network models the Generalized Cost Function has traditionally been evaluated on a link-by-link basis; system-wide effects have not been included in any of the cost terms. For Egypt, however, this limitation was not possible to justify in the Intercity Model. Questions of investment and maintenance of the vehicle fleet, and allocation of the available fleet to competing commodities, are highly significant in assessing Egyptian intercity transport performance and costs. These are system-wide considerations, and our models of Egyptian transport policy have treated them in the Generalized Cost Function as dependent upon network, rather than individual link, characteristics.

Some examples of the types of policies influencing supply of transport services (in terms of transportation performance and costs) that could be considered within the Intercity Model are as follows:

*Within the Intercity Model user choice is represented by the selection of the least-cost available path among all modes (accounting for both link and fleet capacity) for each commodity between each origin-destination pair.

1. Restoration or expansion of highway, rail or waterway capacity: e.g., new link construction; rehabilitation of deteriorated links; upgrading of links to improve geometry or structural strength; changes in enforced weight limits; or lengthening of daily operating hours.

2. Restoration or expansion of available fleet capacity: e.g., replacement of the existing fleet; purchase of additional new vehicles; adjustments in permitted operating speed; elimination of empty backhauls; improvements in vehicle maintenance and overhaul.

3. Changes in price/service characteristics: e.g., adjustments in tariffs; revisions in operating schedules or points of the intercity network served by a carrier; conveyance of goods under fixed contract.

4. Encouragement of, or responses to, changes in the economic situation surrounding transportation: e.g., relative inflation in fuel prices; increases in costs of construction, maintenance and operations seen by owners and operators; revisions in the overhead structures of industry groups.

(b) Innovative Aspects

Several models have been developed to predict transport system performance and costs resulting from the actions of different transport or economic policies. Among these works are the Harvard-Brookings model [Roberts (1966) and Kresge and Roberts (1971)], an integrated model for the surface freight transportation industries [Friedlaender (1976)], the Transport Network Model [CACI (1980)], and the Freight Network Equilibrium Model [Friesz et al. (1981)]. From an analytical perspective the Intercity Model contains several innovative features. These special characteristics are highlighted below, and will be

developed and explained more fully in the technical sections of the paper:

1. In computing equilibrium between demand and supply, the Model employs a simultaneous (in lieu of a sequential) procedure to solve the generation, distribution, modal split, and assignment problems. This approach guarantees a unique, convergent solution for a general network situation (including congestion and capacity constraints).

2. Link costs (composing the Generalized Cost Functions) are estimated by simulation models in lieu of closed-form relationships. These models permit a detailed investigation not only of costs, but also of transport system performance, encompassing both the condition of the system and the level of service provided to users. The simulation models illuminate transport options available to the different actors involved: owners of the transport links (e.g., highway, railway, and waterway authorities), operators of transport services (e.g., truck and bus companies in both public and private sectors, railway authority, public and private barge companies), and users of the transport system (passengers of different income levels, shippers of various commodities).

3. The simulation models permit an explicit treatment of fleet capacity constraints -- i.e., the inability to satisfy latent demand because of shortages of operable vehicles. This issue is distinct from that of link congestion (arising from volume/capacity effects on speed and flow). Mathematical treatment of fleet capacity, and options to remove capacity constraints through fleet investment and maintenance, were designed for the Model because of the severity of this problem among many surface modes in Egypt.

4. The effects of transportation policies are simulated as changes in one or more variables within sets of performance and cost equations, or as changes in sets of constraints upon these equations (e.g., the route structure of different operators). In this way the Model is able to treat not only different kinds of transport policies (investment, maintenance, operating, pricing), but also the interactions among them.

5. Multiple copies of the transport network are maintained simultaneously to address different aspects of the problem. For example, the "actual" network simulates the impacts of link investment, maintenance, upgrading, and rehabilitation; the set of "subsector" networks represents the route structures (i.e., available paths in the actual network) served by different transport operators over time; and the set of "composed" networks represents the paths available to each commodity or passenger class during equilibration.

6. The information needed to support this analytical approach is extensive and detailed. Data have therefore been organized within a hierarchical structure, in which components of the transport problem may be assembled in logical fashion. Aside from the planning capabilities of the Intercity Model itself, the creation of an organized body of information on the transport network is viewed as a very beneficial by-product of this research for Egypt.

2. TRANSPORT DEMAND

The formulation of transport demand within the Intercity Model is based on concepts of user utility and accessibility as discussed, for example, by Dalvi and Martin (1976), Ben-Akiva and Lerman (1977), Williams (1977), and Daganzo (1979). Therefore we simply describe below the qualitative aspects of the demand models; a more formal presentation is given in Appendix A.

The demand models include equations to predict trip generation, trip distribution, and traffic assignment (including, implicitly, modal choice). The formulation of these models follows traditional methods in this area, with the exception of the definition of the transportation network upon which the demand is estimated (and for which transport equilibrium is computed in Section 4).

We assume that each user type chooses the operators and the operator routes such that his total perceived cost (i.e., disutility) from the centroid of origin to the centroid of destination is minimized. Implied in this assumption is the possibility of transfer from one operator to another in the middle of any given trip.

To present this assumption analytically we create a "composed network" for each user type, as illustrated in Figure 1. A given composed network consists of a number of subsector networks* (which are feasible for that user type) connected together through the loading and unloading "links" of that user type to and from those subsectors. We assume that loading/ unloading and (thus) transfers between subsectors may occur at zone centroids only. Of course, different possibilities

*A "subsector" refers to a particular operator; the concept will be explained more fully in Section 3. A given subsector network consists of the set of network links over which that subsector operates.

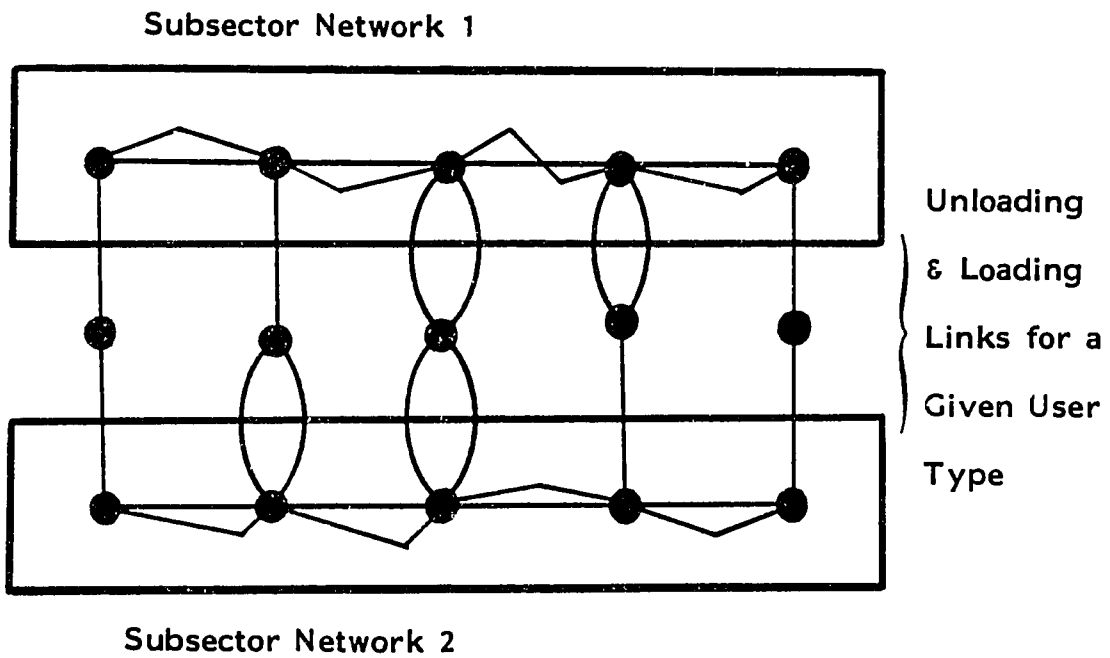

Figure 1. Example of a Composed Network

exist at different centroids depending on how the composed networks are defined.

Actually, the composed network is one of 3 copies of the transport network maintained in the Intercity Model. The need for multiple copies of the network arises from the different types of transport policies, and the different requirements among constituent analytical procedures, that are incorporated within the Model. For example, the "actual" transport network, denoting physical links, link characteristics, and current link condition, is used to simulate link investment and maintenance policy and speed-flow relationships (including congestion) for all vehicles using that mode. (Separate networks are defined for the highway, railway, and waterway modes.) "Operator" networks denote that subset of a given modal network served by a particular operator (e.g., a bus or truck company). Operator networks are thus useful in representing changes in route structure over time. Finally, the "composed" networks represent the sets of operator networks (both linehaul links and loading/unloading links) available to each commodity (i.e., separate networks, as pictured in Figure 1, are defined for each freight and passenger class). Composed networks are applied in predicting demand and in computing transport equilibrium (Section 4).

3. TRANSPORT PERFORMANCE AND COSTS

(a) Background

To assess the implications of transport policy alternatives, the Intercity Model requires estimates of transport performance and costs for various physical and operating components of the intercity system. These performance and cost data are provided by a set of computational models at different levels within each of the intercity modes considered -- highway, rail, and inland water transportation. These models are referred to collectively as the "link cost models".

The models are structured around three categories of actors within intercity transportation:

1. Owners -- those who control transport infrastructure (e.g., Roads and Bridges Authority, Egyptian Railway Authority, and Waterways Authority in Egypt).
2. Operators -- public or private entities which employ vehicle fleets to transport people or goods (e.g., trucking companies, bus companies, auto owners, taxi owners, Egyptian Railway Authority, barge companies).
3. Transportation users -- those who, by their production or consumption of goods, or their need or desire to travel themselves, generate demand for transportation.

Within this framework the link cost models compute the costs and the impacts of four types of transport policies: investment (in both links and fleets), maintenance (of both links and fleets), operations (e.g., scheduling, allowable operating hours, allowable speeds, weight limits), and pricing (tariffs, loading and unloading charges).

(There are also economic scenarios governing, for example, the relationship between financial and economic costs, and rates of relative inflation. These aspects will not be discussed in this paper.)

Owners have responsibility for link investment, maintenance, and operations (allowable speed), and all such policies and results are organized under them in the link cost models. Operators have responsibility for the actual transport of people and goods, and act at a "sector" and "subsector" level within a mode. At the sector level the Intercity Model recognizes the operator's responsibilities for fleet investment and maintenance. At the subsector level the Intercity Model characterizes those operator actions directly perceived by the user -- level of service and cost of transportation.

For example, within the rail mode, if a number of locomotives and coaches were dedicated to passenger service, this set of vehicles would define a "passenger sector" for the rail operator. If the operator then used this equipment to provide both express and local service (or any other types of service distinguishable in some way, including price), these service categories would define subsectors. One can also think of public and private trucking, or the different intercity bus companies, as defining different sectors, each containing one or more subsectors. Policies such as the portion of the network over which an entity operates, scheduling, tariff structures, and load factors can be specified at the subsector level, and relevant costs and impacts will be computed by the link cost models at this level as well.

The actual flows experienced over the transport network result from individual decisions taken by all the potential users of the transportation system -- decisions taken on the basis of the transportation

"costs" perceived by the different users, and the choices available to them. The level of "costs" and available choices result directly from the owner and operator policies above, and are composed within Generalized Cost Functions serving the role of transportation supply functions defined over each link of the network. Values of each term within the Generalized Cost Functions are also estimated by the link cost models.

A complete discussion of the link cost models would be too lengthy for this overall Model description. Instead, we have selected particular models to illustrate the approach used. Details on all models developed for the highway, railway, and waterway modes are contained in the report by Markow, Brademeyer, and Touma (1983).

(b) Owner Cost Models

As indicated earlier, owners provide the infrastructural elements required to accommodate the existing and anticipated traffic volumes, axle loads and sizes of transport means (e.g., vehicles, trains, barges, etc.), and to connect different socio-economic centers (thereby affecting regional and national development). They are mainly concerned with the capacity and condition of the infrastructure, and are involved in the construction, upgrading and maintenance of different elements of their respective networks.

The interaction between owners' policies and the behavior of other actors in the system is evident. Improving the condition of existing linehaul links (or building new ones) affects travel speeds (and hence travel times) and trip reliability, and thereby encourages operators and users to use the "improved" system (or take advantage of the new "access" provided). Consequently, the improved elements would tend to

deteriorate faster (as a function of their usage), requiring more attention to be paid to improved maintenance programs in order to decelerate the deterioration rates of such elements, and so on. The same logic may be said about terminal areas, transhipment points, canal locks, and other elements of the physical network.

In simulating owners' behavior and costs it is necessary to account for these interactions through a set of technical relationships that predict system deterioration as a function of structural strength, usage, age, environment, and maintenance policy. For highways and railways this deterioration represents damage or weakening of the pavement or track structures, respectively. For canals, deterioration results from the combined effects of erosion and siltation. To give an example of the kinds of relationships developed, consider the case of highways.

Deterioration models for highway links have been derived from the relationships employed in the Highway Cost Model [Moavenzadeh and Brademeyer (1977)]. The road condition is represented by a Road Condition Index (RCI) ranging from 0 to 1 depending on the amount of patching and cracking, the roughness, and the rutting present in the pavement. Within each year, and for each link in the network, we predict the change in RCI (i.e., the drop in its value at the end of a given time period as compared to that at the beginning of that period) as a function of the pavement strength (measured by its modified structural number SN) and imposed traffic loads (measured by the number of daily equivalent standard axle loads, or ESAL), and a Maintenance Quality Index (MQI):

$$\Delta RCI = -475 \cdot ESAL \cdot (1+SN)^{-9.36} \cdot (10-MQI)/5 \qquad (1)$$

The MQI is defined on an arbitrary scale from 10 (excellent maintenance) to 0 (no maintenance). To introduce the effect of relative changes in maintenance quality on highway link deterioration, we assume in Eq. (1) that the existing situation in Egypt corresponds to an MQI of 5.

Since the strength of the pavement (denoted by SN) is a direct result of investment policy, Eq. (1) represents an explicit interation among investment and maintenance policy, and road usage. (Factors accounting for soil or climate may also be included.) Furthermore, the time at which particular investment or maintenance actions should be invoked can be controlled by the planner using the Intercity Model in a number of ways (e.g., depending upon calendar time, threshold traffic levels, condition of the road in terms of RCI) to simulate realistic decision-making situations in the future.

Companion sets of models for railway and waterway estimate costs of each link investment or maintenance action in terms of financial, economic, foreign exchange, and taxation components.

(c) Operator Cost Models

Structuring of Transport Operators

Transport operators are defined within the Intercity Model as simulated entities that provide transportation services by deploying vehicles at some charge to users. Each intercity mode considered -- highway, railway, and waterway -- may be visualized as consisting of one or more operators. Exactly how modes should be partitioned into operators depends upon the types of policies one contemplates testing, the detail of analysis desired, and the availability of supporting data.

An example of how operators may be structured in Egypt is given in Table 1. Operators are characterized as "sectors" of a mode, with each sector consisting of one or more "subsectors". Sectors and subsectors are used within the Intercity Model to reflect different aspects of transport operator responsibility. At the sector level we assign responsibility for fleet investment and maintenance; different sectors therefore imply separate fleets. At the subsector level we assign responsibility for deploying the available fleet to provide some level of service to users at some charge. In choosing between two subsectors (within the same sector) a commodity may perceive different tarifrs, travel times, route structures, trip reliabilities, levels of comfort, and so forth.

Modal sectors and subsectors are key building blocks of the Intercity Model, dictating the structure of additional technical, economic and financial information on transport operations. For example, for each sector in Table 1 one specifies data on fleet composition, rates of deterioration, investment and maintenance policies, and costs shown in Table 2. For each subsector in Table 1 one provides data on operations and user charges as shown in Table 3.

Examples of Models

An operator is concerned with increasing the available carrying capacity of his own fleet through a set of operating, investment and maintenance policies for the fleet components. In addition, he is concerned with pricing, scheduling, and vehicle composition which would result in different types and levels of service, with the ultimate objective of maximizing his net profit and/or market share (if private sector) or meeting social and economic objectives (if public sector). Which set of policies to implement is not a trivial issue since his

Table 1. Structuring of Transport Operators Within the Case Studies

MODE	SECTOR	SUBSECTORS
Highway	Auto	Auto
	Taxi	Taxi
	Intercity Buses:	For Each Company:
	East Delta Company West Delta Company Middle Delta Company Upper Egypt Company	Lux Service Normal Service
	Truck	Truck
Railway	Railroad	Diesel Train Service Express Train Service Local Train Service Unit Freight Trains Mixed Freight Trains
Waterway	Barge Transport	Sugar Company Public Companies

Table 2. Data Provided for Each Operator Sector

1. CURRENT FLEET COMPOSITION
   - Number of Fleet Components
   - Age Distribution
   - Availability Function
   - Cost Per New Component
   - Financing Period and Rate
2. DESCRIPTIONS OF POTENTIAL FLEET POLICIES
   - A. Purchases
     - Quantity
     - Cost Per Component
     - Age of Purchased Component
     - Threshold (In Fleet Condition) at Which Purchase Considered
   - B. Replacement
     - Replacement Formula
     - Cost/Salvage Value
     - Age of Replacement Components
     - Threshold at Which Replacement Considered
   - C. Sale/Scrappage
     - Components to be Sold/Scrapped
     - Price Received Per Component
     - Threshold at Which Sale/Scrapping Considered
   - D. Routine Maintenance Costs

Table 3. Data Provided for Each Subsector

1. ASSEMBLY OF COMPONENTS INTO VEHICLES
   - Load Factors
   - Crew Costs per Hour
   - Fuel Costs per Liter
   - Percent Empty
   - Daily Operating Hours
   - Speed Factor
2. OPERATING ROUTE STRUCTURE
3. LOADING/UNLOADING ATTRIBUTES
   - Mean Delay
   - Standard Deviation of Delay
   - Percent Loss and Damage
4. SCHEDULES
5. CONTRACTS

ultimate objective is heavily dependent on the users' responses to alternative actions of different operators.

Several types of link cost models are included at the operator level to simulate the costs and impacts of these different options. These models fall under the generic categories of fleet availability (simulating investment and maintenance policies), and fleet operations (simulating fuel consumption and crew costs). For brevity in this paper, we refer the reader to an extensive description of fleet investment-maintenance relationships by Moavenzadeh, et al. (1983). Some aspects of the computation of travel time (the basis of crew and fuel costs) will be given in the discussion below of user cost models.

(d) User Perceived Cost Models

Users are concerned mainly with the levels of service (performance) of different elements of the system influencing linehaul travel times, waiting delays (e.g., at terminal, loading and unloading facilities), service reliability, out-of-pocket fares, discomfort (for passengers), loss and damage (for freight shippers), congestion, and lack of available transport due to fleet capacity. In general, all of these performance measures are functions of owners' and operators' policies as well as the usage of the system. In this section we will describe how the users perceive the combined effects of these actions (by owners, operators and users) on the system's performance.

The idea is to convert each of the performance measures into monetary costs and combine them into Generalized Cost Functions reflecting users' perceptions of the system in generalized cost terms. Such models predict the average perceived costs per unit of flow for different user types on different elements of the system.

For a given set of owner and operator policies, user cost is a functions of the volume and pattern of system usage, which differ from one link to another. Also, by definition, levels of service differ among subsectors. In addition, the perceptions of costs of using a given subsector on a given link differ from one user type to another. Thus, we define a user cost model (as a function of flows on the system) for each user group, subsector and link on the network. Let b denote a subsector, k denote a commodity (or passenger) type and a denote a link on the network. Then a user cost function may be expressed as follows:

$$C_a^{kb} = TF_a^{kb} + TTC_a^{kb} + TRC_a^{kb} + DC_a^{kb} + FCC_a^{kb} \qquad (2)$$

where:

C_a^{kb} = average perceived cost per unit of flow of commodity k traversing link a using subsector b;

TF_a^{kb} = tariff (or out of pocket cost) incurred by k to travel along a by b;

TTC_a^{kb} = travel time cost perceived by k to travel along a by b;

TRC_a^{kb} = time reliability cost perceived by k to travel along a by b;

DC_a^{kb} = loss and damage (or discomfort) cost as perceived by k on a by b; and

FCC_a^{kb} = fleet capacity constraint cost as perceived by k on a using subsector b.

Below, we look into some of the above cost items, indicating the basic assumptions involved in their calculation and the policies which might be reflected through their values. For more detail the reader is referred to Markow, Brademeyer, and Touma (1983).

Travel Time Cost

Travel time cost is calculated by multiplying the average travel time by a coefficient representing value of time to convert it into monetary cost units:

$$TTC_a^{kb} = VT^k \cdot E\,[TT_a^{kb}] \qquad (3)$$

where:

VT^k = value of time for commodity k; and

$E\,[TT_a^{kb}]$ = expected travel time of commodity k traversing link a by subsector b.

The value of time is a function of the commodity (or passenger) characteristics. This information is exogenously estimated and input to the model.

The average travel time is assumed to be function of the flows of all commodities using all subsectors traversing the link under consideration. This is a realistic assumption because of the interactions among commodities and vehicles traversing the same link. A given commodity may be carried by different vehicle types which have different operating speeds; thus, the expected travel time of that commodity is a weighted average of travel times of these vehicle types. Because of congestion, the travel time of a given vehicle is dependent on the number of vehicles using the same link. A given vehicle may carry different commodities and its number will depend on the flows of those commodities using it.

Commodities are allocated to vehicles in proportion to their respective available capacities, p_v^k, computed as the ratio of available hours for commodity k on vehicle v to the total number of vehicle hours available for commodity k on all vehicles. In calculating available vehicle hours we take explicit account of the number of available vehicles within the fleet (a function of fleet investment and maintenance policy), the load factors of each commodity on each vehicle, the speeds of the vehicles, the available operating hours per day of each vehicle, and the proportion of time during which each vehicle is empty (all manifestations of transport operating policies).

The expected vehicle travel time is given by the following equation:

$$E\,[TT_{av}] = TT_{av}(o) + [TT_a^{car}(o) \cdot \ell_a\,(V_a)/(1-\ell_a\,(V_a)] \qquad (4)$$

where:

$E\,[TT_{av}]$ = expected travel time of vehicle v on link a;

$TT_{av}(o)$ = free flow travel time of vehicle v on link a; and

$\ell_a\,(V_a)$ = a given function reflecting the congestion effects of all vehicles on link a (V_a) on travel time of vehicles v.

Then we calculate the expected commodity travel time as an average of vehicle travel times using the proportions of allocation as weights:

$$E\,[TT_a^k] = \sum_v E\,[TT_{av}] \cdot P_v^k \qquad (5)$$

Free flow travel time is dependent on the maximum operating speed (set by operators and/or traffic flows) and the condition of the road, track or canal (determined by owner investment and maintenance policies and the usage of the system). Congestion effects are reflected through utilization factors [ℓ_{av} (V_a) for all a,v], and are dependent on the total traffic on the link under consideration.

Fleet-Capacity-Constraint Cost

Fleet capacity constraint is a characteristic of the fleet components at the sector level, but is perceived by commodities (and passengers) at the subsector level when the required fleet to accommodate their flows exceeds the available fleet allocated to diffferent subsectors. The problem is a serious one and cannot be ignored in the Egyptian intercity transport system, where fleet capacities of railway and waterway operators are severly constrained.

Transport equilibrium models in the past have not explicitly included the effects of fleet capacity constraints. As far as we are aware, no definitive solution to the problem exists so far. Nevertheless, we have attempted to provide a "reasonable" solution by letting commodities (and passengers) perceive very high costs on those subsectors which cannot accommodate their current demands. Consequently, portions of those demands may shift to other subsectors which may be more expensive but presumably have excess carrying capacities. These adjustments in the flow patterns of different commodities and passengers will be done iteratively

through the equilibrium prediction process (see Section 4) until we arrive at a state of equilibrium where demands on different subsectors are practically feasible and at the same time in accordance with assumptions describing users behavior in the system.

The fleet-capacity-constraint term in the link cost function is based upon the calculation of a fleet capacity ratio, denoting the capacity used vs. the capacity available for commodity k in subsector b. The fleet capacity ratio is affected by operator's fleet policies and the usage of the system. For instance, fleet investment and maintenance policies determine the availability of different fleet components; however the use of this available fleet to accommodate anticipated traffic is dependent on a set of operating policies such as the allocation of components to different subsectors (within the sector), use of those components to compose vehicles (within the subsector), loading capacities of different components, scheduling policies and contracted flows. All of these policies are taken into consideration when we calculate the required capacity to accommodate given demands. Dividing the required capacity by the available yields the fleet capacity ratio. This ratio is then transformed into a perceived effective cost (or monetary penalty), using some value (or cost) associated with commodity k traversing link a using subsector b (e.g., market values of commodities, or some measure of strategic or social value or perishability).

4. TRANSPORT EQUILIBRIUM

Transport equilibrium is the interface between demand and performance; its prediction is at the core of the analysis of transportation systems. Existing approaches that involve sequential solutions of the generation, distribution, modal split, and assignment stages yield results that need not be internally consistent. Because of the interdependence between demand and performance (due to congestion and capacity constraints), the performance or demand levels that one assumes as inputs to any one stage in the process need not agree with those that one determines as outputs from other stages. This deficiency suggests predicting demands and performance of all problem stages simultaneously.

Research intended to meet this objective began as early as 1956 and has been extensive during the 1970's [e.g., Beckman, et. al., (1956), Bruynooghe, et. al., (1968), Leblanc (1973), Evans (1976), Florian and Nguyen (1978), Asmuth (1978), Aashtiani (1979), Aashtiani and Magnanti (1981), Smith (1979), Defermos (1980), Sheffi and Daganzo (1980)]. A detailed review of these studies by the author (Safwat) identified the tradeoffs between the theoretical (behavioral), technical (convergence) and practical (computational efficiency) aspects of the equilibrium problem. None of these studies has been successful in addressing all aspects of the problem. In this research we have attempted to strike a balance among the theoretical, technical and practical considerations of the problem, to develop an equilibration procedure that has a unique solution that can be computed efficiently by a convergent algorithm, and to apply this prodcedure in a practical way to the Egyptian intercity transport system.

(a) A Simultaneous Transportation Equilibrium Model (STEM)

The basic assumptions on demand and performance functions of the Egyptian intercity system have been introduced in Sections 2 and 3 respectively. The equilibrium problem may now be stated as follows:

"Predict generated traffic, network distributions of traffic flows, and associated travel costs for all links (a), subsectors (b), and commodities (k):

1. Simultaneously;
2. With a procedure that converges to an equilibrium (proven to exist and to be unique); and
3. Efficiently (in the computational sense)."

The proposed approach to resolve this problem is to formulate an Equivalent Optimization Problem (ECP), show that ECP has a unique solution that is equivalent to that of (STEM), solve (ECP) with a convergent algorithm ("Shortest Path to Nearest Destination," or SPND), and test the efficiency of the (SPND) algorithm. Notice that the equilibrium model (STEM) may be solved directly (e.g., as a system of non-linear equations, or variational inequalities) but either convergence will be slow even for small systems, implying that such procedure may be practically infeasible for large-scale networks; or, there will be no guarantee of convergence even though such procedure would be practically feasible and efficient. The proposed approach aims at achieving both convergence and efficiency simultaneously.

(b) An "Approximate" Equivalent Convex Program (ECP)

The Equivalent Convex Program (ECP) is formulated in terms of an optimization problem in Appendix B. Three basic observations about the

ECP optimization problem provide useful insights. The first is that all the constraints are linear. The second is that the objective function is strictly convex and thus ECP has a unique solution provided that C_a^{bk} is convex for all a, b, and k. Third, ECP is exactly equivalent to STEM provided that the Jacobian matrix of the user cost function

$$\nabla C(F) = \left[\frac{\partial C_a^{bk}(F)}{\partial F_{a'}^{b'k'}}\right] \tag{6}$$

is symmetric (where C represents user costs as a function of flows F for commodity k on link a in subsector b). The symmetry assumption is valid in cases where there is no interaction among different user types in the system or where the congestion effect of different user types on each other is identical. In practice, however, users do interact and their cross effects may not be exactly identical, implying that $\nabla C(F)$ is, in general, asymmetric, and hence ECP becomes "approximately" equivalent to STEM.

The first and second observations imply that ECP is a convex program (i.e., minimizing a convex function subject to a set of linear constraints) which has a unique solution - a great advantage as far as computational procedure and convergence are concerned. The third, undoubtedly the most important observation, implies that solving ECP yields a unique equilibrium for STEM.

(c) The Simultaneous Prediction of Equilibrium

The proposed algorithm to solve ECP belongs essentially to the general class of feasible-direction methods and in particular to the Frank-Wolfe approach of direction-finding. The algorithm is called "Shortest Path to the Nearest Destination" or (SPND) as dictated by its procedure. It is guaranteed to converge to an equilibrium and is expected to be computationally efficient.

Beginning with an initial feasible solution, any feasible-direction method generates a sequence of feasible solutions. At a given iteration the method involves two main steps. In the first step, a direction for improvement is determined. In the second, an optimum step size along that direction is determined. The current solution is then updated and the process is repeated until a convergence criterion is met.

Three comments are now in order. The first is that the determination of an optimum step size along a given direction involves solving a one-dimentional minimization problem for which there are well-known standard algorithms such as Golden-Section and Bolzano Search [see, for example, Zangwill (1969)]. The second is that there is no standard procedure for determining a feasible direction. The third comment is that the above method may not always converge. Thus, since we have chosen to solve ECP with a feasible-direction method, there are two main challenges to face, namely the efficient determination of direction for improvement at each iteration and the guarantee of convergence.

As far as convergence is concerned, we know that ECP is a convex program and hence, any feasible-direction method will converge to its optimum solution. In fact, this is one of the main reasons for choosing this method. As far as direction-finding is concerned, Safwat (1982) has developed a procedure based on the Frank-Wolfe approach which is expected to be computationally efficient. In fact, it is this direction-finding procedure that distinguishes the SPND algorithm from any other one.

5. APPLICATIONS

The Intercity Model is now being applied in a series of case studies within Egypt. In these cases we are examining the transport cost and performance implications of different investment, maintenance, operating, and pricing policies; moreover, these implications can be assessed from the viewpoints of the several actors involved (owners, operators, and users), and in financial, economic, foreign exchange, and taxation measures.

Several categories of information are available from the Intercity Model through the analysis period:

USER-RELATED INFORMATION

1. Origin-destination matrix (produced for each commodity);
2. Surplus-deficit reports (produced for each commodity);
3. Commodity transport statistics (produced for each commodity);

OPERATOR-RELATED INFORMATION

4. Fleet investment/maintenance summaries (produced for each vehicle component within a sector of a mode);
5. Operating statistics (produced for each operating subsector of a mode);
6. Consolidated sector report (including combined effects of investment/maintenance and operations, and comparison to revenues; produced for each sector);

OWNER-RELATED INFORMATION

7. Technical condition and performance of each link (produced for each mode: highway, railway, waterway); and
8. Link investment/maintenance summaries (produced for each mode).

Therefore it is possible to conduct in-depth studies of the impacts of transport policy on shifts in both demand and supply. Moreover, it is possible to do intermodal comparisons, say, of investment vs. total transportation output; or, within modes, to compare ratios of capital or operating costs to total costs. Cross subsidies can be identified among operator subsectors or among commodities within a single subsector. In short, many interesting aspects of transport policy analysis (particularly within a developing country context) can be conducted with the Intercity Model.

Our case studies in Egypt will be considering the impact of transport policy in light of the general development goals which Egypt has set for itself. For example, a review of 5-year development plans and supporting documents has identified several broad-based and long-term goals in Egypt, including the redistribution of income, more uniform distribution of population, promotion of the private sector, an increased emphasis on rail as a viable mode of transport, completion of projects already started, and greater maintenance and rehabilitation of the existing fleet and transport physical plant. Using the Intercity Model, we will be testing different combinations of investment, maintenance, operating, and pricing decisions in the highway, railway, and waterway modes to assess their consistency with the development objectives above, and their differential impacts upon owners, operators, and individual classes of users. These cases, conducted in cooperation with Cairo University and the Egyptian Ministry of Transport, will be completed over the coming year.

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APPENDIX A

DEMAND MODELS

(a) Trip Generation

Trip generation is treated as a function of national and regional socio-economic activities, socio-economic characteristics of the user, and performance of the transport system. More specifically, we assume that trip generation is given by a general linear model with the measure of accessibility as one of its variables:

$$G_i^k = \alpha^k S_i^k + \sum_{\ell=1}^{L^k} \alpha_\ell^k f_\ell^k (E_{\ell i}^k)$$

$$= \alpha^k S_i^k + E_i^k, \qquad \text{for all } i, k \tag{A.1}$$

where:

G_i^k = number of trips of user type k generated from i;

S_i^k = accessibility of origin i perceived by user type k;

$E_{\ell i}^k$ = value of the ℓth socio-economic variable that influences trip generation of user type k from origin i;

$f_\ell^k (E_{\ell i}^k)$ = a given function specifying how the ℓth socio-economic variable, $E_{\ell i}^k$, influences trip generation of user type k; and

E_i^k = the composite effect of the socio-economic variables, exogenous to the transport system, on trip generation of user type k from origin i.

The quantities α^k and α_ℓ^k are coefficients to be estimated.

(b) Trip Distribution

Trip distribution is given by the well-known "logit" model:*

$$T_{ij}^k = G_i^k \frac{\exp(-\theta^k U_{ij}^k + A_j^k)}{\sum_{m \in D_i^k} \exp(-\theta^k U_{im}^k + A_m^k)}, \quad \text{for all } i,j,k \qquad (A.2)$$

where:

T_{ij}^k = number of trips of user k traveling from i to j.

U_{ij}^k = the "generalized" cost of travel from i to j as perceived by user type k;

A_j^k = the composite effect of the socio-economic variables, exogenuous to the transport system, on trip attraction of user type k at destination j.

*Derivation of the logit model may be found in many references such as Dominchic and McFadden (1975), Ben-Akiva and Lerman (1977).

D_i^k = the set of destinations which are perceived by commodity k at origin i, to be accessible

The quantity θ^k is a coefficient to be estimated.

(c) Modal Split and Traffic Assignment

The user optimization principle (i.e., the basic assumption of ownself minimization of disutility) implies that the total perceived costs on all used paths* (on the composed networks) between a given origin-destination pair are equal and less than those on unused paths, i.e.:

$$C_p^k = \sum_{a \varepsilon A^k} \delta_{ap} \cdot C_a^k \begin{cases} = U_{ij}^k & \text{if } H_p^k > 0 \\ > U_{ij}^k & \text{if } H_p^k = 0 \end{cases} \quad \text{for all p} \qquad (A.3)$$

where:

C_p^k = the total average perceived travel cost of user type k on some path p on the composed network of that user type;

$$\delta_{ap} = \begin{cases} 1 & \text{if link "a" on the composed network belongs to path p on that network;} \\ 0 & \text{otherwise;} \end{cases}$$

A^k = the set of links on the composed network of user type k; and

*A path on the composed network represents some subsector-route combination on the actual network.

H_p^k = the volume of flow of user type k along path p on its composed network.

(d) Calibration of Demand Models

For each user type k we need to calibrate a trip generation model and a trip distribution model. Calibration implies model specification and coefficient estimation. Specification involves the choice of variables to be included in the model and their functional forms. Theoretically, model specification should be based on some theory of behavior. Practically, however, it is constrained by the availability of, and the ability to measure, "desirable" variables. Estimation of the coefficients of the trip generation model (i.e., α^k and E^k) and the trip distribution model (i.e., θ^k and A^k) may be achieved in two steps. First, one estimates the coefficients of a logit distribution model assuming fixed trip generation. Second, one estimates the coefficients of a general linear regression trip generation model with S_i^k for all origins calculated from the distribution model calibrated in the first step. Actual calibration of demand models is currently underway at Cairo University based on data provided by NEDECO (1981).

APPENDIX B

OPTIMIZATION PROGRAM TO SOLVE FOR EQUILIBRIUM

Consider the following optimization problem:

$$\text{MINIMIZE } Z = J(S) + \Psi(T) + \phi(H) \tag{B.1}$$

SUBJECT TO:

$$\sum_{j \in D_i^k} T_{ij}^k = \alpha^k S_i^k + E_i^k, \qquad \text{for all } i,k \tag{B.2}$$

$$\sum_{p \in R_{ij}^k} H_p^k = T_{ij}^k, \qquad \text{for all } i, j, k \tag{B.3}$$

$$S_i^k > 0, \qquad \text{for all } i, k$$

$$T_{ij}^k > 0, \qquad \text{for all } i, j, k \tag{B.4}$$

$$H_p^k > 0, \qquad \text{for all } p,k$$

where:

$$J(S) = \sum_i \sum_k \frac{1}{\theta_k} \left[\frac{\alpha^k}{2} (S_i^k)^2 + \alpha^k S_i^k - (\alpha^k S_i^k + E_i^k) \ln (\alpha^k S_i^k + E_i^k)\right] \tag{B.5}$$

$$\Psi(T) = \sum_{i,j} \sum_k \frac{1}{\theta_k} \left[T_{ij}^k \ln T_{ij}^k - A_j^k T_{ij}^k - T_{ij}^k\right] \tag{B.6}$$

$$\phi(H) = \sum_{a,b} \sum_k \int_0^F C_a^{bk}(w)\, dw_a^{bk} \tag{B.7}$$

$$F_a^{kb} = \sum_{i,j} \sum_{p \in R_{ij}^k} \delta_{ap} \cdot H_p^k, \qquad \text{for all } a, b, k \tag{B.8}$$

The objective function Z comprises three sets of terms. The first set has as many terms as the number of origins of different user types (commodities) in the network. Each term, $J_i^k(S_i^k)$, is a function of the accessibility variable S_i^k of a given origin $i \varepsilon I^k$. The second set has as many terms as the number of origin-destination pairs of different user types in the network. Each term, $\Psi_{ij}^k(T_{ij}^k)$, is a function of the number of trips T_{ij}^k distributed from a given origin $i \varepsilon I^k$ to a given destination $j \varepsilon D_i^k$. The third set has as many terms as the number of links in all the composed networks. Each term, $\phi_a^k(H)$, is a function of the flows of all user types over <u>all</u> paths which share a given link $a \varepsilon A^k$ (as implied by the link-path incidence relationship (B.8).

The constraints (B.2) are as many as the number of origins of different user types, and may be referred to as production constraints. A given constraint in (B.2) states that the number of trips of user type k distributed from a given origin $i \varepsilon I^k$ to <u>all</u> possible destinations $j \varepsilon D_i^k$ should equal the total number of trips generated from that origin.

The constraints (B.3) are as many as the number of O-D pairs in the network. A given constraint in (B.3) states that the number of trips over all paths from a given origin $i \varepsilon I^k$ to a given destination $j \varepsilon D_i^k$ should equal the total number of trips distributed from i to j.

The constraints (B.4) are as many as the number of decision variables of the optimization problem, and may be referred to as the non-negativity constraints.

The equations (B.8) are called the link-path incidence relationships. A given equation in (B.8) states that the total flow of a given user type k traversing link $a \varepsilon A^k$ using subsector b is the summation of the flows of that user type over all paths (on its composed network) which share that link.