Management System for Transport Infrastructure

ANTTI TALVITIE

No network level management models have been developed for new investments in transportation facilities to improve access, increase capacity, or achieve socially desirable goals. Yet investment takes 40 to 80 percent of the road budget, and its share of other modes is not negligible. Two or three road network design models aimed at this objective have been proposed. A model is described having the dual objective of network design and comprehensive, multimodal transport investment. The proposed model suits the management structure and style of most transport agencies because it is based on hierarchical decision making and considers investment trade-offs between regions, functional classes of roads, most important modes of transport, and other road expenditures. The model incorporates multiple criteria and multiple objectives, and it focuses comprehensively on policy rather than unimportant technical details of demand and supply models. These important attributes are lacking in other available transport investment models, which are either macroscopic or multimodal but not both.

In Figure 1 is the design of the Finnish Highway Administration's road and bridge management system (*1*). It has three parts: development, rehabilitation, and routine maintenance. Development consists of new investments or marked improvements in highway level of service. Rehabilitation means periodic reinvestment and maintenance of existing roads and pavements. Routine maintenance refers to snow and ice removal, care of roadside and service areas and traffic signs and markings, and other minor actions to keep pavements smooth and safe. This three-part division reflects the policy and budget-making practices of most transportation administrations, not only of highway agencies, and corresponds to the time horizon of decisions: development for the long range, rehabilitation for the intermediate range, and routine maintenance for the short range.

There are three administrative decision making levels, shown compactly as rows in Figure 1, in each road program area. The first, the network level, deals with policy and is usually exercised by the central management in the administration or the ministry. The second, the project level, is normally performed by the district office's engineers charged with execution of the policies and deals with design. The third, the program level, lies between the network and project levels and is the joint responsibility of the central administration and the district offices. Its function is to program the actions over years to implement the policies set at the network level—the multiyear road program.

The model discussed in detail in this paper belongs to the upper left hand box in Figure 1. It is designed to help in decisions about how much, in what region, for what mode and service type (national or local), and when new transport investments should be made. These kinds of decisions are strategic long-range choices and may be expensive; attached to comprehensive pricing, tax, and environmental reforms or policies; or otherwise have large impacts on users, the environment, and the national economy. For this reason the decision-support systems for investment strategies must consist of models that are broad in scope.

The approach presented is new. Instead of the traditional link-level transport systems analysis appropriately suited for project-level development decisions, the models chosen are input-output and capital budgeting formulations sometimes used in analyzing government allocation of resources to different industrial sectors of the economy. The discussion that follows is couched in terms of a country, but the model could be applied on a larger scale where the question is in what country or region, for what mode, and on what level (national or local) should transport investments be made.

The system of models described does not replace project planning tools. What is needed by management, and what the present model provides, is the ability to analyze new transport investments, operating subsidies, or comprehensive taxation and pollution controls in large domains or categories and assess the likely benefits and costs of such actions.

GENERAL STRUCTURE OF THE TRANSPORT DEVELOPMENT MANAGEMENT SYSTEM

Requirements

In pavement management systems and maintenance management systems, the logical objective is to minimize the highway agency plus highway user costs, subject to a budget and road condition constraints. Models with such objective function have been implemented (*2,3*). The optimization in these models also solves for the optimal level of service. This is an important characteristic because the agency level-of-service standards may not be optimal but simply engineering conventions. It is essential to preserve this constrained optimization in all the models to allow trade-off of monies between the three domains—development, rehabilitation, maintenance—to gain the useful interpretations of an optimum.

A second required feature of the system is multimodality: highway (including bus), rail, and air. Multimodality, which also implies consideration of both passenger and freight traffic, is necessary because of questions about rail construction in place of highways and busways, and because the value of travel time makes air ever more attractive to long-distance passengers and high-valued freight.

A final requirement is to include all important policy considerations and their interrelationships in a comprehensive manner in a "block" structure, whereby "blocks" of objectives or constraints can be added as knowledge becomes available and new issues emerge.

The questions addressed are where—not which—links should be constructed, for what mode, in what (regional) order and extent,

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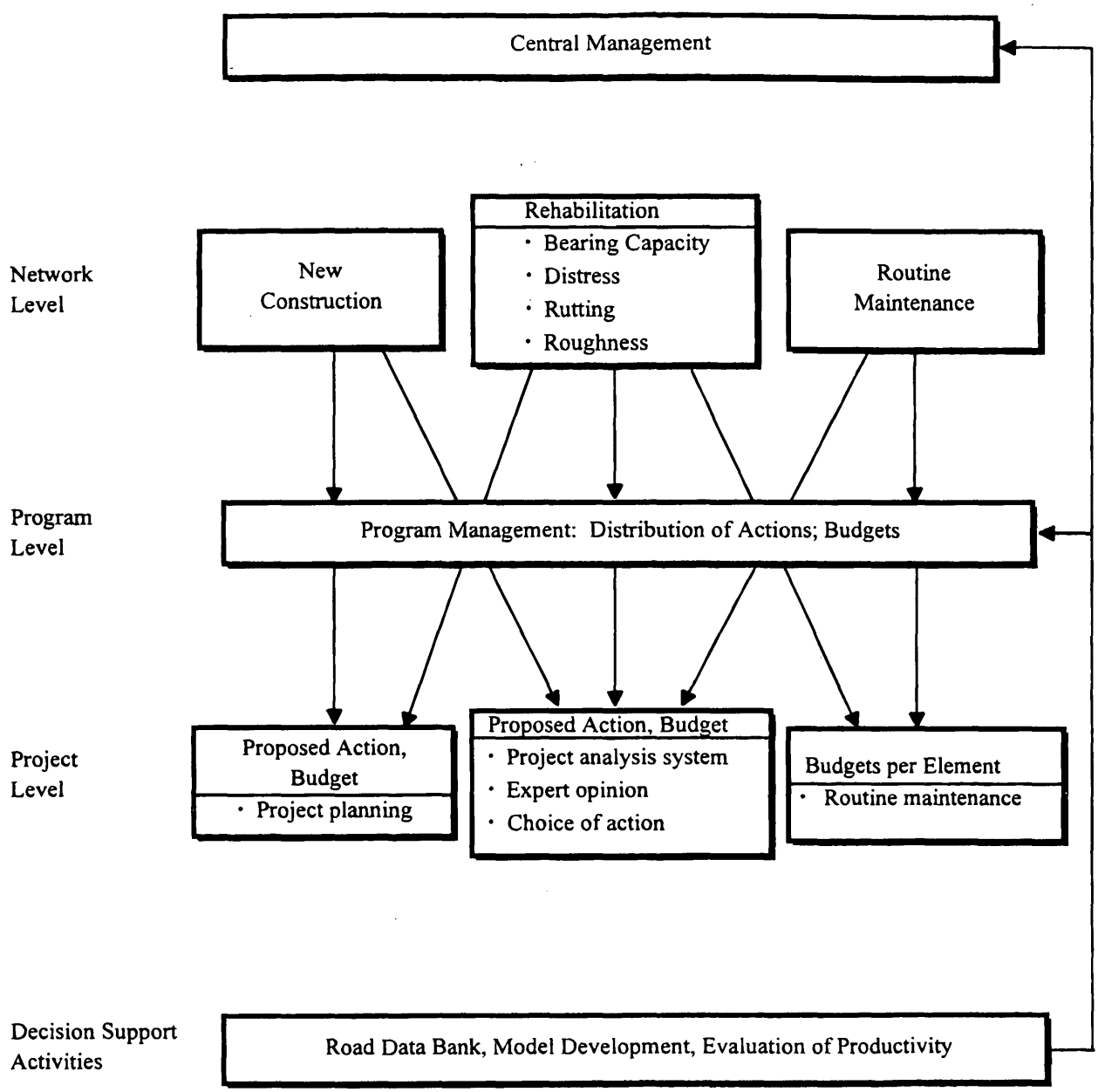

FIGURE 1 Highway agency investment and maintenance models.

when, and whether there should be other conditions (e.g., pricing, subsidy, etc.) attached. Because transport system planning is also driven by social objectives—regional policy, employment policy, environment, taxation, and so forth—their inclusion in the model is necessary. A model system satisfying these requirements is formulated as the constrained minimization of total transportation costs. Figure 2 shows the model framework; it has a comprehensive, block-type structure that can be developed in stages by many actors [see also Morlok et al. (*4*)].

The remainder of this section presents a mathematical representation of the model system, describing most important factors involved. Notation is given in Table 1. It is recognized that every concern is not addressed, but a much larger number of important considerations than are incorporated into the present models are addressed as shown in Figure 3. The transport development management system (DMS) provides a useful and consistent framework for analyzing economic, social, and environmental impacts of all transportation expenditures.

After presenting the model, the policy variables available in the model will be once again reviewed.

Objective Function

The objective function minimizes the fixed facility, operating, user, and pollution costs of transportation, subject to constraints. The minimum cost point is zero: when there is no traffic, no transport facilities are needed. There are three types of fixed facilities: highway, airline, and rail (water can be added, if desired). On each of these fixed facility networks several types of transportation service

Relationships	Common Carrier Vehicle Movements and Capacity	Road Design	Fares and Tolls	Demands	Effectiveness Measure
Minimizing total annual costs	Cost	Cost		Cost	
Subject to					
Technological limitations	Performance	Performance		Flow quality	
Demand functions	Level of service	Level of service	Level of service	Flow quality	
Effectiveness: Profit	Cost	Cost	Revenue	Revenue Cost	Minimum profit
Effectiveness: Capital budget	Cost	Cost			Maximum expenditure
Effectiveness: Accessibility	Level of service	Level of service	Level of service		Accessibility objectives
Effectiveness: Social state	Level of service	Level of service	Level of service		Social state objectives

FIGURE 2 General structure of optimal multimodal network operations model.

TABLE 1 Notation

Sub- or superscripts (lower case letters designating variables):

i = investment; y = rehabilitation; h = routine maintenance
r = region number
k = functional highway class (1=main, 2=regional, 3=local)
t = capital cost type (1=fixed facility, 2=terminal, 3=equipment)
m = fixed facility mode (1=highway, 2=air, 3=rail)
s = service type
for m=1 car, s=1 auto alone, s=2 carpool,
truck s=3 local truck, s=4 regional truck,
bus s=5 local bus s=6 regional bus
for m=2 air, s=1 to/fr Helsinki, s=2 regional, s=3 freight
for m=3 rail, s=1 national, s=2 regional, s=3 freight
e = emission type l = lower bound u = upper bound

Decision Variables and Constants (capital letters)

Q = existing highway capacity - e.g. lane kilometers
C = additional, new highway capacity
K = Q + C
M = existing fixed facility capacity on common carriers (eg.railkm)
N = new fixed facility capacity on common carriers
L = level-of-service attributes (V, P, F, access distance)
F = frequency of service, V = speed of travel, P = price of travel
D = demand, pass/ton/vehicle kilometers (per day or year)
CO= car-ownership
PO= pollutants emitted
E = occupancy (pass/vehicle, tons/vehicle, train)
B = budget constraint

G, T, A = demand generating, distributing, attracting attributes
S = socioeconomic attributes
FC, FT = maximum available flow capacity on common carrier links, terminals
LF= load factor

Parameters and Coefficients (lower case letters defined further by sub- or superscripts)

c = facility, operating, user variable or fixed cost (e.g. FIM/facilitykm per year)
a = pollution cost (FIM/vehicle km)
μ = pollution emission rate (pollutants per vehicle km)

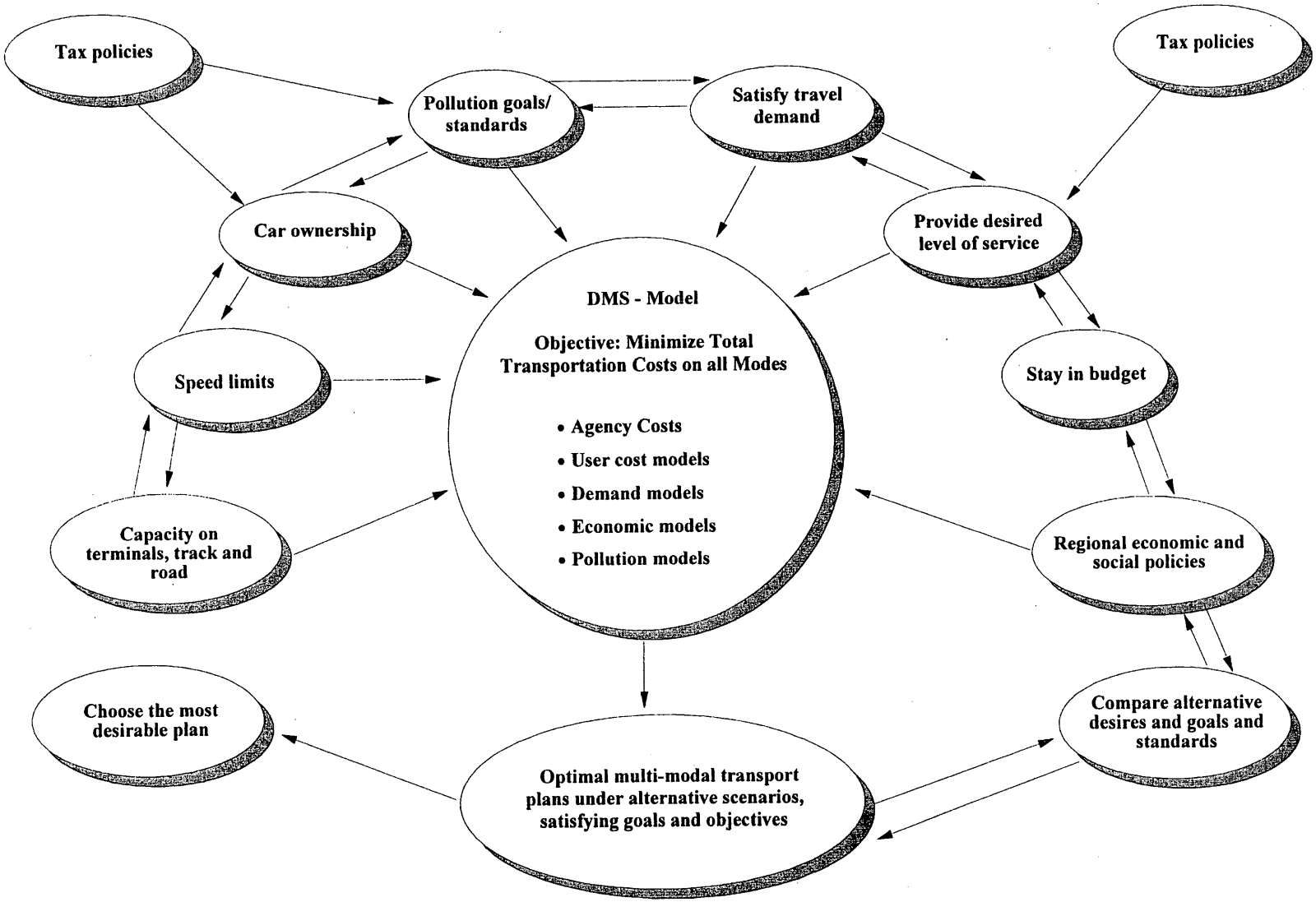

FIGURE 3 Decision-making considerations modeled in DMS.

are provided (e.g., drive alone, carpool, local truck, regional truck, local bus, and regional bus on highways).

The fixed facilities costs of highway consist of three components: capital costs of building new roads or lanes, rehabilitation and periodic maintenance costs of existing roads, and costs of routine maintenance. These costs, and the operating and user costs, are expressed separately for three functional classes: main highways, regional highways, and local roads, each represented in terms of kilometers of lanes and covering all public roads. The operating costs for cars and trucks are calculated as a function of vehicle kilometers of travel, and vehicle size composition. In this way, for instance, an optimal allocation of funding among road classes can be determined (Figure 4).

The size of the network, in terms of lane kilometers by functional class, is one of the decision variables in the model. Thus, the model indicates whether the size of the highway network is too small or large, economically speaking. This is especially important in developing countries, where road expenditures often take a sizable percentage of gross domestic product (GDP). Equally important, the size of the network (by region) can be set as a constraint, that is, the present network will not be abandoned. However, that will have repercussions on the level of service provided on important links. Too large a network will also reduce the budget available for rehabilitation and maintenance and worsen the condition of existing roads.

The fixed facilities costs of the common carrier modes (bus, rail, and air) are also of three kinds: new investment, rehabilitation, and maintenance costs. They can further be broken down into terminal, equipment, and network costs. (It may be expedient to add some of the common carrier cost components together for simplicity if the objective of the model is to focus upon highway development.) The fixed facility costs of the bus mode consist of the terminal costs;

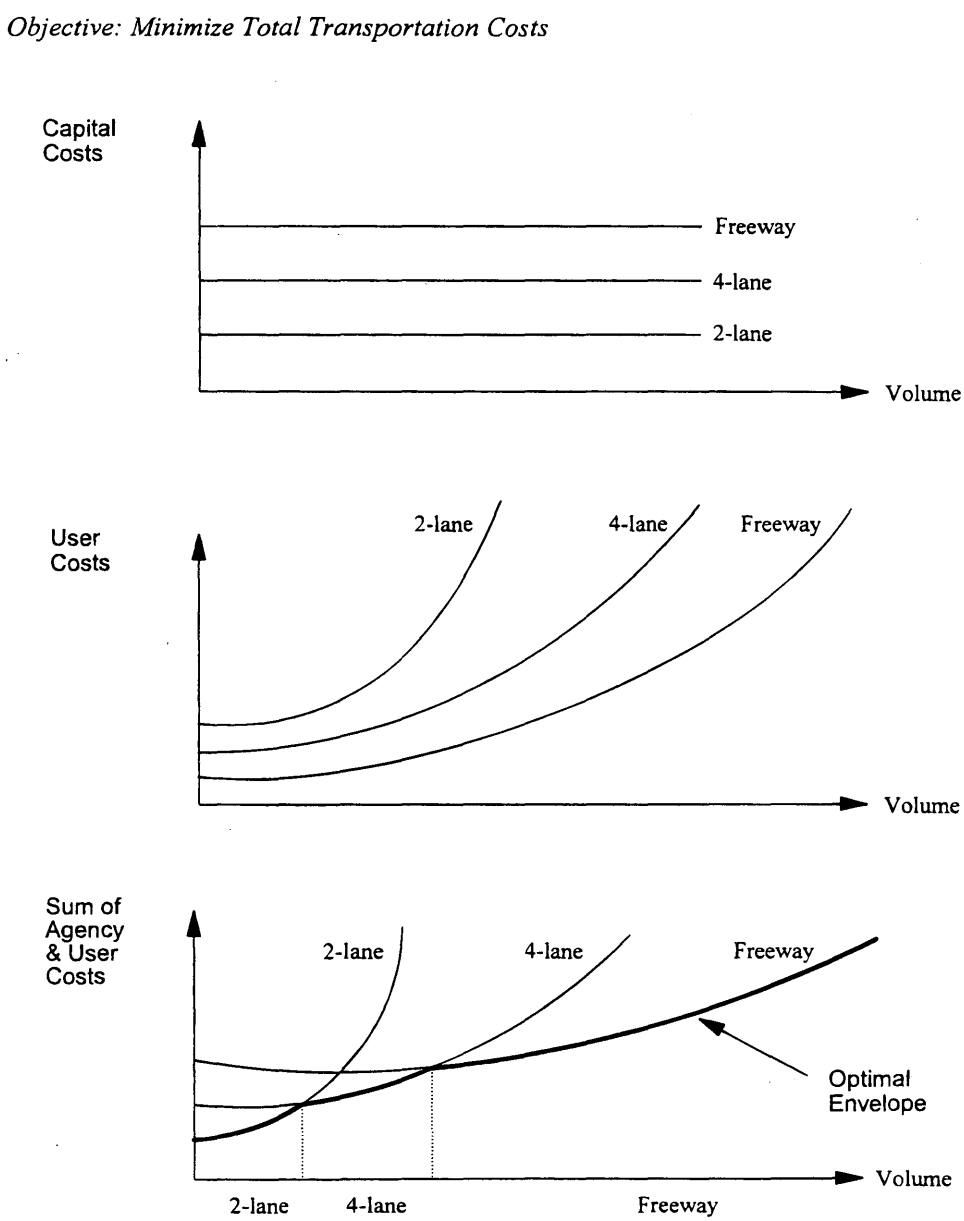

FIGURE 4 One-mode illustration of principle (no budget or other constraints).

there also are equipment costs, which can, but need not, be included as part of the operating costs. The rail network is represented by kilometers of rail lines, terminals, and equipment appropriate to the technology used. For air there are runways, terminals, and equipment.

Operating costs on common carriers with fixed vehicle size (bus, air) and costs on common carriers with variable vehicle size (train, air) can be expressed as a function of route mileage, service type and frequency, and vehicle size, if necessary. The operating costs for bus are proposed to be calculated for two service types: regional and local. Rail has three service types: national, regional, and freight. The air mode also has three service types: national (continental), regional, and freight (national/continental only).

The user costs are calculated as a function of demand. The automobile user costs are, furthermore, divided into two groups: variable (trip) and fixed (capital) costs. Both the variable and the fixed costs can be made to be a function of vehicle size and age distribution. One feature of this division is the ability to model car ownership decisions explicitly, which permits the evaluation of alternative car ownership–car use taxation policies.

If environmental costs (due to pollution, for example) are available, they can be included in the objective function (as done in Table 2) and their effect on the optimal system assessed. The same applies to accidents, which are included in user costs in the present formulation.

To accomplish geographic distribution of costs (and benefits), the country or continent is divided into regions. The number is arbitrary. The number of regions to be used in the model is primarily dependent on the availability of necessary cost information for highway and nonhighway modes and the administrative structure of the country. By using a small number of zones and avoiding link-level representations, the models give a broad-brush representation of the transportation system.

Demand Function Constraints

Travel drives up costs because travel demand must be satisfied. A direct demand model (Table 3), with vehicle or passenger/ton kilometers of travel as the dependent variable, is the forthright alternative for several reasons. First and foremost, flow—vehicle or passenger kilometers of travel rather than trips—is a useful output measure that can be related to resource requirements. Second, models with flow as a dependent variable can include all the typical and important travel demand model attributes in one equation: mode attributes (time, cost, frequency), traffic generating and attracting characteristics (population, employment, industrial structure), and trip distribution and trip length variables (land use pattern, degree of urbanization, activity density, and so forth). The third reason for using passenger/

TABLE 2 Objective Function (Summation over Subscripts)

Highway Fixed Facility Costs, m=1:

$\Sigma^{mi}c_{kr}C_{kr}$	+	investment cost; ${}^{mi}c_{kr}$ unit investment cost of m=1, C_{kr} lanekm of highway of class k in region r
$\Sigma^{my}c_{kr}Q_{kr}$	+	rehab cost; ${}^{my}c_{kr}$ unit rehab cost of m=1, Q_{kr}=lanekm of existing highway; class k, region r
$\Sigma^{mh}c_{kr}K_{kr}$	+	maintenance cost; ${}^{mh}c_{kr}$ unit maintenance cost of m=1, $K_{kr}=C_{kr}+Q_{kr}$, lanekm of highways; class k, region r

Air, and Rail Fixed Facilities Costs, m=2,3:

$\Sigma^{mi}c_{mtr}N_{mtr}$	+	investment cost; ${}^{mi}c_{mtr}$ unit investment cost, N_{mtr} amount of new capital investment of type t (t=1, km; t=2, terminals; t=3 equipment) in region r
$\Sigma^{ym}c_{mtr}{}^{m}M_{mtr}$	+	rehab costs of existing facilities ${}^{m}M_{tr}$; type t, region r
$\Sigma^{hm}c_{mtr}{}^{m}K_{mtr}$	+	maintenance cost; ${}^{hm}c_{tr}$ unit maintenance costs, $K_{mtr}=M_{mtr}+N_{mtr}$, fixed facilities; type t, region r

Note: Formulation allows reduction in capacity, important for rail. May require constraints on Q and M for acceptable solutions.

Auto and Truck Operating Costs, m=1:

$\Sigma^{os}c_{krs}{}^{s}D_{krs}/E^{s}$	+	auto and truck operating costs, m=1, s=1,2,3,4 ${}^{os}c$ operating costs of service type s, ${}^{s}D_{krs}$= travel demand on m=1, s=1,2,3,4; s=1 auto alone, s=2 carpool, s=3 local truck, s=4 regional truck, s=5 local bus, s=6 regional bus; E_s=vehicle occupancy

continued on next page

TABLE 2 *(continued)*

Bus, Air, and Rail Operating Costs, m=1,2,3:

$\Sigma^{oms}c_{msr}{}^{ms}F_{msr}{}^{ms}M_{msr}$	+	common carrier operating costs, m=1 (bus,s=5,6), m=2 (s=1,2,3), m=3 (s=1-3), F=service level (frq/day), M=routekm; service types s; bus: regional, local; air and rail: national, regional, freight

Note:nonlinearity present, FxM. Tentative solution: express the costs additively, c1 marks per departure, c2 marks per vehicle/ train kilometer, and assume that service type accounts for vehicle size, if not then use nonlinear programming. Other possibilities exist also to preserve linearity, for example fix M for each plan and optimize F.

Variable User Costs:

$\Sigma^{ums}c_{krms}{}^{s}D_{krms}$	+	user costs, ${}^{ums}c_{krs}$ unit user cost by mode and service type

User Fixed (auto-, truck ownership) Costs:

$\Sigma^{ao}c_rCO_r$	+	auto-ownership costs, ${}^{ao}c_r$ costs of owning a car, AO_r auto-ownership in region r
$\Sigma^{bo}c_rBO_r$	+	truck-ownership costs, ${}^{bo}c_r$ costs of owning a truck, BO_r truck ownership in region r

This formulation of user costs, as variable and fixed costs, allows the evaluation of alternative auto and truck tax strategies.

Pollution Costs:

$\Sigma^{rms}a_{rkms}D_{rkms}/E_{ms}$	+	modal pollution costs by service type, a unit cost of pollution, D=travel demand; E=vehicle occupancy

ton kilometers of travel as a dependent variable is simplicity. Major advantages are gained because origin-destination flows need not be predicted and the network can be defined in a schematic manner. The demand models themselves will have a simple specification because the generation/attraction variables are combined. Other advantages are that many policy consequences (e.g., pollution) depend on kilometers of travel and trip length, and less on the number of trips.

The justification for this kind of model is threefold: first, most trips are intraregional, not interregional; second, the objective of the model is to guide and help decide (yearly) investments by mode, region, and modal (highway) functional class, not by specific links; and third, the consequences of alternative policies and investments can be modeled and accounted for directly. Direct demand models of the type described above can be entered as constraints: demands must be satisfied consistent with the level of service users are willing to pay for.

Profit and Budget Constraints

The standards of design and level of service must be paid for, and it is be useful to examine the consequences of such standards on goals at an early stage of policy planning. There always exists a scarcity of resources. Profit and budget constraints bring the financial reality into the model (Table 4). These constraints are self-explanatory and require no basic research, only clarification of the costs that must be covered by the revenues from users and, in case of highways, definition of revenues collected. Alternative taxation policies can also be formulated as part of these constraints. A negative profit (that is, a subsidy) can also be formulated as a constraint.

The importance of being able to examine different budget levels and cost recovery levels by mode and their consequences for taxation and user charges and social goals cannot be overemphasized. Using the present models, the budget levels and user charge deliberations are done without knowing what will be done with the monies, how specific policies will affect the usage of transport facilities, and what social impacts they may have. The contrary is also true. Transport planners normally examine their plans without knowing what kind of user charges or subsidies are implied by their proposals, what trade-offs between modes and between programs are presupposed, and so forth. In short, budgets, user charges, and subsidies are considered too late in the transportation planning process.

Accessibility and Technological Constraints

Technological constraints are imposed to help define the set of feasible solutions. They take the form of physical limitations on the

TABLE 3 Travel Demand Models

In generic form the travel demand (model) constraint takes the following form:

$$^{ms}D_r \geq {}^{ms}g(G_r, A, T, S_r, {}^{ms}L_r)$$

where:

$^{ms}D_r$ = demand on mode m, service s, region r passenger/ton/vehicle kilometers

G_r = demand generating variables in r; G(population, employment, industrial structure)

** industrial structure = manufacturing/farming,forestry/service, gvt/ recreation, tourism/energy, constr/

A_r = demand attracting characteristics in r and outside r; the same variables as in G

S_r = socioeconomic attributes of people residing in r; S(Income, Auto-ownership, Family structure, Occupation structure, Age structure, maybe others)

$^{ms}L_r$ = Level-of-service attributes of modes and services available in r; L(in-vehicle travel time/speed, access time/distance, travel price/cost, and frequency)

T_r = Travel demand distributing attributes in r; T(land use)

** land-use pattern = pop/emp density urban/rural; per cent urban; no of cities, area, etc.

Note: It is also possible to formulate a car-ownership model; it would have many of the demand model S variables in the RHS. In that case it would become meaningful to enter car-ownership as a cost in the objective function. (Note: costs of trains and buses are there also; of course, the capital costs of cars could be included in the cars' operating costs in the objective function. The present formulation of the objective function separates the auto user costs into variable and fixed costs; a preferred formulation.)

The car ownership constraint could be of the form:

$CO_r \geq$ F(Income, Family structure, Occupation structure, Price of cars, Land-use pattern, Level-of-service)

Note: $AO_r = POP*CO_r$. It is advantageous if CO is not equilibrated, but entered directly as a constraint (and as a cost; values of L, if needed, are easiest obtained directly from constraints). The identity equations for auto time equilibrium conditions must be added here. Auto travel time is non-linear but that should cause no trouble.

performance of the transport system or vehicles. All transport modes have a lower bound for travel time because of speed limits or technology limitations; an upper bound can be specified if desired to reflect level-of-service objectives.

These constraints exhibit the standards desired by the travelers or the society. Accessibility can be defined in many ways. The simplest approach is recommended: a combination of level-of-service attributes (door-to-door travel time or speed, frequency of service, and door-to-door cost) afforded by modes in a region by functional class or service type. Accessibility objectives may also be defined for some specific city pairs, or to some important points such as ports, or to the national and regional capitals. Accessibility can be used as an effectiveness measure to evaluate alternative networks.

Pollution objectives can be accounted for by defining upper bounds of vehicle emissions (perhaps together with availability and cost of such vehicles). When pollution cost trade-off analyses are desired, the associated costs must be included in the objective function. If strict pollution standards are assigned to cars, there can be difficulties in modeling the car fleet composition; however, the model system structure imposes no restrictions or difficulties.

A technological constraint is needed for capacity. The capacity of links in a particular functional class must be equal to or greater than the demands on that class; consistency with the travel time constraint must also be maintained. Overall, areawide travel speed-capacity relationships need to be estimated to formulate an area-based equilibrium condition.

Typical technological constraints require only token research for highway modes and for air. The most difficult problem is, perhaps, the condition of the equilibrium on the highway network because it will have to relate travel demand, the vehicle kilometers of travel per area, to capacity, lane kilometers of highway per area. Nonetheless, a reasonable formulation for the equilibrium condition is not likely to be difficult to find. A sample of technological constraints is given in Table 5.

TABLE 4 Budget and Profit Constraints

Budget Constraints

$\Sigma^{i}c_{kr}C_{kr} + \Sigma^{y}c_{kr}Q_{kr} \leq$ Highway Investment Budget (for each r if desired)

$\Sigma^{h}c_{kr}(C+Q)_{kr} \leq$ Highway Maintenance Budget (for each r if desired)

$\Sigma^{mi}c_{rt}{}^{m}N_{rt} + \Sigma^{my}c_{rt}{}^{m}M_{rt} \leq$ Common Carriers' Budget Constraints, m=2,3

$\Sigma^{mos}c_{rsm}{}^{s}F_{rsm}{}^{s}M_{rs} + \Sigma^{mh}c_{rt}{}^{m}M_{rt} - {}^{m}p_{rs}{}^{m}D_{rs}$ (Farebox Revenue)

$\leq$ Common carriers' Operating Subsidy Constraints m=1,2,3 (for each s if desired)

Naturally, all the constraints can be summed up for a grand total transportation budget.

Profit Constraints

$\Sigma^{ms}p_{rk}{}^{ms}D_{rk}$ + subsidy $\geq$ Costs to be covered, even by r and k if desired

Note: The price of travel ${}^{ms}p_{rk}$ (mk/pass.ton.veh.km) may have to be modified into a form p+boarding fee.

Constraints on auto taxation policies, impacting the auto variable and fixed costs can be added here when desired.

Social State Constraints: Preliminary Ideas

Social state constraints, which relate to economic development, can assume a wide variety of interpretations. The inclusion of these constraints depends heavily on what is available. The main idea is to couple network level of service, or investment, in a particular mode and region with social characteristics, such as population growth (decline), employment growth (decline), environmental quality of an area, or profitability of an industry. The problem here is to find and develop such (linear) relationships. For example, if an input-output table is available, preferably by region (but not an interregional one to keep matters simple), impacts of road expenditures on employment by industrial sector and on incomes can be estimated. Input-output relationships are often simple and suffer from uncertainty, but an order of magnitude estimate can nonetheless be obtained. This is an important extension of the traditional transport models in view of the fact that the road administrations are normally asked to take on tasks that are well beyond moving people and goods. These tasks as a rule are related to broad social objectives on poverty, economic development, equity, and the like.

PROBLEMS AND RECOMMENDED SOLUTIONS

The key practical problems requiring resolution are the dynamic short-term/long-term model interface and network aggregation. These two problems are the Achilles' heels in every single mode-optimizing investment model; in DMS the problems are compounded by the existence of many fixed facility modes, many types of transport service on these fixed facility modes, and multiple objectives. The short/long term interface and the network aggregation problems were studied to ascertain that a feasible procedure exists for DMS.

The optimizing model is very straightforward. It minimizes the sum of user and agency costs—the total transport costs—subject to constraints for a given year. The formulation of the model was approached in the following manner: several alternative fixed facilities plans—aggregate networks as defined earlier—are formulated for the time period under consideration. The optimum refers to their optimal capacity and optimal operation in that time period, subject to chosen (or alternative) pricing and taxation policies, service levels, and other constraints. In principle one could optimize the fixed networks for every 5- or 10-year interval and then draw an optimal path through time. There may be other alternatives. The proposed approach necessarily forces consideration of short-term pricing, level of service, and budget policies. This way of solving the time dependent problem is formulated and discussed in the next section.

Spatial network aggregation must be done to keep the model management oriented. One way of doing this is to include only the main highway network, or only its most important parts, as explicit physical links, and to aggregate the rest of the network as a composite link per zone/zone pair. Another alternative, traditional

TABLE 5 Constraints on Accessibility and Technology

Accessibility and Technology

${}^{lm}V_{ksr} \leq {}^{m}V_{ksr} \leq {}^{um}V_{ksr}$;	upper and lower bound on travel speed
${}^{lm}P_{ksr} \leq {}^{m}P_{ksr} \leq {}^{um}P_{ksr}$;	upper and lower bound on travel cost
${}^{lm}F_{sr} \leq {}^{m}F_{sr} \leq {}^{um}F_{sr}$;	upper and lower bound on frequency
$\Sigma^{erm}\mu_{ks}{}^{rm}D_{ks} \leq {}^{erm}PO$; allowed in	pollution constraint, ${}^{erm}PO$=max emissions region r, mode m, ${}^{e}\mu$=emission rate of type e.
$K_{kr} = C_{kr} + Q_{kr}$;	capacity identity, total=new+existing, m=1
$K_{tr} = N_{tr} + M_{kr}$;	capacity identity, total=new+existing, m=2,3
$\Sigma^{mr}D_{ks} \leq \Sigma^{mr}K_{ks} \times {}^{mr}LF_{ks}$;	capacity must be more than demand in each region, LF is a capacity/ equivalency factor. **Note**: K=M for common carriers

On common carriers, of which rail is the only one of concern, the vehicle flow capacity must exceed train frequencies.

$\Sigma^{mr}F_s \leq {}^{mr}FC$	${}^{mr}FC$ is the maximum flow capacity on rail, m=2, region r

Terminal capacity constraint may have to be added here for Helsinki airport; and if rail becomes really popular for it, too.

$\Sigma^{mr}F_s \leq {}^{mr}FT$	${}^{mr}FT$ is the terminal capacity of mode m, air and rail, region r

Additional accessibility constraints may be formulated case by case. For example, lower bound constraints may be desired for Q_{kr} (i.e. highways will not be closed) and $M_{mtr,}$ (bus routes, rail lines or airports will not be closed); constraints may be desired on C_{kr} and N_{mtr} (i.e. certain investments will be made); even some socioeconomic attributes S_r, and demand generating/ attracting attributes G_r and A_r may be constrained from below or above to indicate social or regional policies. Travel demand distributing attributes T_r, may also be constrained from above or below to signal land use controls or regional policies.

network-link/O-D-trip specific formulation, was also examined. Both would have caused unmanageable problems with the demand models, because demand on the main links could not be forecast accurately enough. Making the zone size smaller allows more accurate link-level forecasts, but it once again makes the problem too detailed for efficient management use. Also, meaningful introduction of the multicriteria constraints would have been in jeopardy.

The most promising alternative was mentioned above. The proposal aggregates networks functionally and uses service-specific travel demand models in which the passenger/freight/vehicle kilometers of travel is the dependent variable. This somewhat unconventional approach gives freedom elsewhere, especially in the introduction and formulation of the technological, environmental, and social constraints. An added advantage of the aggregate demand/ supply formulation is the ability to include all traffic in the model.

This type of aggregate formulation serves the decision makers and the top management well. It forces them to think and define the problems in terms of goals and objectives and costs of their achievement. It defers the traditional network-link/trip specific technical problem to that level of planning and administration where it can be appropriately addressed in an established technical paradigm: network (link) alternatives ↔ prediction ↔ participation by affected interests ↔ evaluation ↔ choice ↔ design ↔ implementation.

SHORT-TERM MODEL

The short-term model was investigated to ascertain that such a model can be developed as a component of the DMS, even though no such model need be formulated as part of the DMS. It is well to remember that most long-term transportation planning models are "horizon" models, normally 20 to 25 years into the future. The transportation plan in these long-term models is couched in terms of network, links and link capacities and link volumes, terminals and the like, prices, and so forth exactly as in the short-term models but, truthfully speaking, merely less accurately (but with same precision). The short-term plan and model are only intuitively related to the long-term plan without any specific implementation path. The long-term transportation plan is normally updated about every 5 years, and the short-term and TSM plan every year or every other year. In practice, the situation is often such that the development of the new long-term plan is started when the present has been

approved. Thus, the absence of a formal short-term model is not a liability of a long-term multimodal investment model because such models, with a real promise in practical applications, have not in fact been formulated and used.

The DMS model offers an opportunity for integrated short-term–long-term formulation that is pragmatic and realistic. It is recalled that DMS does not specify what links, where and with what capacity, but rather what level of service, on what fixed facility, by what means, and in what approximate geographic area. Important components of uncertainty are thus accounted for or avoided by relaxing the geographic, timing, and modal precision of the long-term plan. Decisions that cannot be made and are not made now are not assumed to have been made.

Mode questions and timing of investments can be more precisely investigated by formulating a short-term DMS model. This is briefly described next. The formulation is a transformation of a network model proposed by Morlok.

DMS is designed to the analysis and design—a synthesis—for several alternative transportation futures. These futures can relate to fixed facilities—investment or abandonment—and terminals, pricing and operating policies, technology, and investment budget. Or, using the notation of this paper (Table 1), the contribution of existing fixed facility and terminal capacities M, Q, FT and FC to costs (new capacities C and N are endogenous in the model); level-of-service attributes F, P and LF (speed V is endogenous); pollution emissions μ; and budgets B can be examined for a horizon year or, for that matter, for any intermediate years.

This approach to long-term planning gives one solution to formulating a short-term model, which, as a bonus, also resolves the nonlinearity problem present in the common carrier part of the (long-term) objective function. The short-term model is most easily described and understood with the aid of Figure 5.

In Figure 5, Targets 1, 2, and *n* represent alternative long-term plans with exogenous specification of Q, M, B, FC, FT, P, and F. (Of these only the first five, existing fixed facility capacities and the budget constraint, are absolutely necessary.) The target plans can be reached several different ways over the 20- to 25-year period. These alternative ways are the potential short-term plans—alternative intermediate fixed facility plans—that can be drafted for various time periods (say, 5, 10, and 15 years from today). Their costs, capacity, level of service, and other consequences can be calculated using the DMS model. Finally, the optimal path to each of the target plans can be computed. This would be the optimal short-term/long-term combination. As shown hypothetically in Figure 5, a long-term plan may have an exclusive optimal development path (e.g., Target 2), or alternative plans may have a partly common optimal development path (e.g., for Targets 1 and *n* the optimal path is the same until 10 years from the present). The communality in opti-

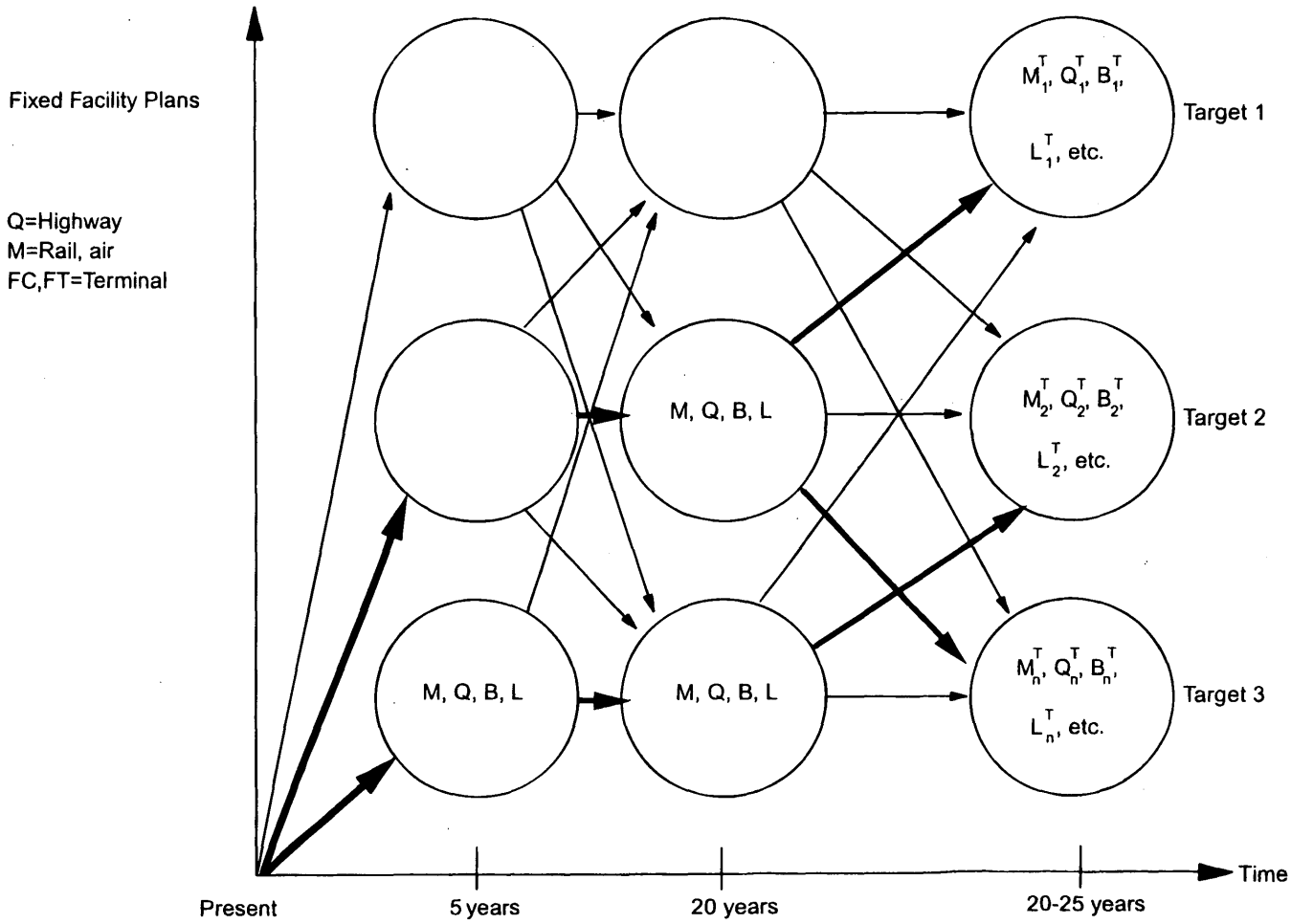

FIGURE 5 Optimal short-term DMS model.

mal paths is an indication of flexibility a plan has in the face of uncertainty; other positive attributes may also be attached to these optimal development paths.

PLANNING PROCESS

All parts of the comprehensive model system lend themselves to a multiplicity of approaches to plan, finance, and implement transportation projects in a variety of organizational settings. Rehabilitation and routine maintenance projects can be identified either by the regional or central organization and carried out either by direct labor or by contract. In a decentralized setting, which is implied and favored, the central administration distributes the resources between programs and regions, suggests the distribution of actions and their budgets, and sets road condition targets for the network. The region chooses the specific links, the specific action to be undertaken and contracts it out, or does it by direct labor. The same applies for routine maintenance and bridges. Of course, it also is possible to "auction" and contract out the entire rehabilitation and routine maintenance program as a whole, or in lots, to private contractors. To define the contracts well, the model system aids the road agency to define the target budget and the target distribution of road condition by volume or functional class that the contractor is expected to deliver.

For investments the situation is more complicated. Again, the function of the central administration is to fix the investment budget (by mode in case of a DOT-type organization) by functional class for highways for each region. Normally there is a national highway plan that is being implemented and there are other links favored or chosen by the road agency. However, recent experience in California and Australia, and elsewhere, suggests that the links or actions chosen by the road agency are not necessarily the ones favored by the private sector. Because only part of the money is earmarked for certain links, the nationally important links, a part is available for choosing those links for which private financing can be leveraged. In this way the public investment can be made to go farther by forming private-public partnerships.

The formation of private-public partnerships and the leveraging of private funds to build transport projects would, of course, lead to a different type of planning process, community participation, and, possibly, land use planning. It would also give the road agency a new role. No doubt, there are other ways in which this type of model system could be used for planning and programming of transportation improvements and for restructuring transport organizations.

CONCLUSIONS

It is emphasized that DMS requires no strict adherence to its recommendations. It merely points out what the cost, environmental, and other consequences are when one path/plan is chosen over others. The strength of DMS is in its simplicity, in the speed and comprehensiveness with which it can analyze the consequences of a multitude of hypotheses about socioeconomics or technology of the future. It also designs an optimal transport plan for alternative future scenarios and permits a timely analysis of a great number of alternative hypotheses or transportation plans without getting bogged down by the details, technical or otherwise.

The DMS formulated in this paper is an innovative tool. The approach presented for transport network design and management is new and well suited for network-level decision making and for transport policy. It is the missing link of the management models and systems developed during the last decade for pavement management and for routine maintenance. DMS is the last piece of the puzzle of Figure 1.

DMS considers new investments in all modes of transport, not only roads. It is a macroscopic management model and does not deal with specific links, terminals, or operating rules, but acts comprehensively at the policy level allowing decentralization of decision making. DMS can incorporate multiple criteria and multiple objectives, in mode specific manner if desired, by relating accessibility and investment to modal demands, to technology and environmental relationships and objectives, to budgets and profits, and to socioeconomic and regional development. Automobile ownership model and taxation policy are examples of social-state relationships already in the model. And as indicated in the text, the model is open to other types of social or regional objectives using, for instance, simple input-output models.

The model also allows assessment of the size of the network by region. In developed and developing countries alike the size of the network is often too large to be economical. Too large a physical plant eats up resources and causes truly important links to be in a poorer condition than required for efficient operation of the system. It is granted that abandonment of lower-level network links is a politically sensitive issue. However, if the true costs and trade-offs of uneconomical links were known, better policies might be devised to achieve similar objectives at a lesser cost.

Finally and very importantly, DMS is integrated with rehabilitation and maintenance actions and their benefits and costs. Because all three components—new investment, rehabilitation/periodic maintenance, and routine maintenance—minimize the sum of user and agency costs by linear optimization of the appropriate objective function, it is possible to perform sensitivity analyses and infer when transfer of funds from one program area to another is warranted in the interest of achieving a global optimum.

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REFERENCES

1. Talvitie, A. P., and R. Olsonen. Selecting Asphalt Concrete Condition States for Highways, Presented at the 67th Annual Meeting of the Transportation Research Board, Washington, D.C., 1988.
2. Thompson, P. D., et al. A Micro-Computer Markov Model for Optimal Pavement Rehabilitation Policy. *Proc., Fifth World Conference on Transport Research,* Yokohama, Japan, 1989.
3. Talvitie, A. P., and M. Miettinen. A Comprehensive Highway Investment Programming System. *Proc., International Conference and Exhibition on Road Transport*, Beijing, China 1989.
4. Morlok, E. K., E. N. Thomas, et al. *The Development of a Geographic Transportation Network Generation and Evaluation Model.* The Transportation Center at Northwestern University, Evanston, Ill. 1970.

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