SYSTEM ANALYSIS OF TRANSPORTATION FORECASTING AND TRANSPORT DEVELOPMENT PLANNING MODELS IN THE USSR

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1. INTRODUCTION

Modeling of transport functioning and development has been intensively carried out in this country since the 1950s. It can be conventionally divided into four stages:

- Initial stage. Formulation of goals, development of models and algorithms for solving partial transport planning problems (search for the shortest routes, rational distribution of freight traffic, development of transportation networks, etc.). The activities involved static linear models, and solution techniques were based directly on classical publications[1-5].

- Model improvement stage. A heavy emphasis is placed on accounting for real transport system properties in modeling: nonlinear characteristics of its components, their dynamics, and nondeterministic character, huge dimension of networks, etc. This was the time of transition from linear to nonlinear models, from static to dynamic ones, and methods of accounting for incompleteness and ambiguity of input information were developed. A brief description of this stage of research can be found in [6-7].

- Stage of systems modeling of transportation processes, when solution of individual partial problems (even on the basis of sufficiently adequate models) gave way to construction of sets of models, where all major interrelated tasks of transport planning are solved with respect to objectives, information, etc. The results of this stage of research have found the widest application in designing automated control systems for individual types of transport and for planning the whole transport system development at the level of the USSR State Planning Committee [8-10].

- Current stage, involves modeling of transport operations in new economic environments associated with restructuring of the national economic management in the USSR.

In fact, the point is about the further improvement of a set of models created at the preceding stage.

2. PRINCIPLES OF TRANSPORT MODELING

The construction of a set of models should be guided by the following basic methodological principles:

1. National economic approach. Railway transport modeling is based on analyzing its contribution to sectoral, territorial, and national economic balances of production and consumption of different products, as well as to solution of social, ecological, and other problems. Most often this is a timely and efficient delivery of cargoes and passengers from points of departure to points of destination.

2. Comprehensiveness. In considering different actions on transport development one should account for the all-round consequences of their implementation (including not only technological, economic but also social and ecological ones) both directly at the transport and outside it. One should also keep in mind that sophisticated technical and economic complexes (including the uniform transportation system and separate components there of, i.e. types of transport, regional lines) are characterized by integrity, self-regulation, and homeostatic behavior. This results in particular, in synergism irreducibility of transport system properties to a sum of individual parts thereof, and calls for taking a comprehensive account of their interaction having a considerable impact on the structure and parameters of railway transport.

3. Accounting for resource scarcity. The total amount of all reproducible and non-reproducible resources at the disposal of society at each given instant in time is limited. Therefore, in assessing measures on transport development, in comparing costs and benefits associated with utilization of resources to that end, it is necessary to secure, in each concrete case, an effect at least equal to that in some other sector of the national economy where these resources could be used to its advantage.

4. Feasibility. The formulated plans of transport development should be realistic , i.e. the goals set should be tied up with the possibility of accomplishing the planned steps with the allocated resources (capital investments, labor and material resources, etc.).

5. Adequacy of description. Transport is a complex multilevel system of material production projects whose large individual sections (railroad, steamship lines, etc.) have their own interests and decision mechanisms including those concerned with development of their production base. Management of such multilevel complexes is quite specific for it ought to account for a certain technological and economic relationship of subsystems. It is, therefore, very important to take account of real (as a rule, nonlinear and variable) characteristics of separate transport systems, their horizontal and vertical communications in the process of operation.

6. Effectiveness. Development of complex transport systems may go along many conflicting ways, and a high resource utilization efficiency is possible only given a thorough consideration of a variety of goal accomplishment alternatives.

For the considered class of systems it is the choice of development alternatives providing for a timely and qualitative freight and passenger traffic at a minimal total national economic cost (with regard to national resources, fixed assets construction and functioning).

The most general case of vector optimization aims at a variety of Pareto optimal alternatives, and a tradeoff scheme determining an effective choice.

7. Dynamism. Under technological change enhancing economic growth, marked structural changes, etc., transportation modeling should account for the time factor: changes in transportation requirements, conditions and modes of transport system operation, relative and absolute value of resources and products, presence of lags, etc.

8. Controllability. Planning of transport development should be viewed as a search for an optimal management of its development during the forthcoming period of time. Note that it is impossible to optimize the structure and parameters of decisions made and implemented in the past. It is possible to influence only the future costs and benefits related to construction and development of transportation projects, depending on managing transport development. One should also account for a number of circumstances: a certain sluggishness and discrete (stagewise) nature of development of many transport systems and projects, necessity of rational capacity reserves, adaptation properties of transport systems, impact of the operating economic mechanism, common and local interests of transport enterprises.

3. STRUCTURE OF A SET OF MODELS

As applied to railway transport, a set of economic and mathematical models encompasses the following major blocks: (a) models for defining future needs in freight and passenger traffic; (b) models of traffic distribution between types of transports; (c) models of transport infrastructure development; (d) models of freight and passenger flows intensity; (e) models of rolling stock reproduction; (f) models defining value parameters of transport functioning.

Formally, the set is a population of interrelated descriptive normal models of different structure: for problem (a) these are balance and statistical dynamic models; for problems (b)-(e) these are dynamic nonlinear (with continuous and discrete variables) networks and point optimization models; for problem (f) these are equilibrium models or dual models of special mathematical programming problems.

In determining the needs for freight traffic with regard to production deployment and product consumption in this country, as well as the established transportation and economic relations, etc. they construct chess tables of correspondence, with respect to major transportation-intensive types of product, whose subsequent mapping on the traffic network produces utilization rate of the network components and the need for its development.

In forecasting the size and direction of passenger traffic, use is made of various regression models (one factor, multiple factor, gravitational and entropy type ,etc.) whose variables are determined by economic, demographic, and other factors.

The optimization problems aim to exercise all necessary freight and passenger traffic most efficiently.

Accordingly, the objective functions of optimization models represent all future discounted profits and costs (nonrecurring and current), for some or other transport development alternatives connected with traffic, development of transport infrastructure, acquisition of new rolling stock, materials and energy resources, remuneration at all stages of transportation process, etc.

The set of constraints includes dynamic limitations on all types of employed resources (investments, energy, labor, ecological, informational) and necessity to meet the transportation needs of customers.

The value parameters of transport system functioning (prices of different types of rolling stock, transportation rates, etc.) represent dual estimates in a general dynamic optimization problem.

Since far from all factors (primarily social and ecological ones) could be strictly and adequately represented in planning models (especially long-range ones) the set of models and the respective forecasting and planning calculations envisage combination of formalizable and nonformalizable procedures operating in interactive mode. In particular, this relates to accounting for technological change whose dynamics is set by experts both during preparation of input information and directly in the process of calculations (by varying the respective economic, technical and ecological characteristics of the rolling stock).

The utilized models are illustrated with two models of a set, one of which relates to blocks(b) and (c),and the second one to blocks(e) and (f). For the purpose of brevity, the models are somewhat simplified as compared to those used for calculations.

4. MODELS OF TRANSPORT NETWORK DEVELOPMENT

Consider the following scalar optimization problem. Let the following variables be known: network and opportunities for changing its topology in the considered period of time;

(b) assumed points and volumes of freight dispatch and destination (or a respective chess table of correspondence) as well as size and routes of different categories of passenger flows; (c) state of all network components at a time of planning, possible stages of reconstruction (or new construction) as well as all required maintenance and economic characteristics making it possible to determine the size of maintenance costs of each considered component of the network (units, junctions, etc.) and capital investments needed for its upgrading to some other level of capacity;

(d) all additionally imposed constraints on centrally allocated resources-labor, material and financial (in particular, capital investments, capacities of construction organizations).

It is necessary to elaborate steps on improvement of the available network components and construction of the necessary new main lines (as well as the respective schedules), with regard to resource constraints, providing for the minimal total national economic costs incurred during the planning period on the network improvement and delivery of cargoes and passengers (given satisfaction of the schedule and quality of transportation).

We shall also assume that:

-the possible states of technical facilities at each component of the network are partially ordered (e.g.with respect to increased capacity), and this ordering is implemented in time, i.e. transition to lower levels is not envisaged;

-the losses in the course of changing the state of components are low, i.e. capital investments required for transition from one state of the component to the other directly or via intermediate states of hierarchical chain differ insignificantly; Network is fully dependent on the available facilities and rate of the companent utilization.

Then the dynamic model with discrete-continuous variables can look like:

$$_{x^t}min_{\eta^t} F(T, X^t, \eta^t) =_{x^t} min_{\eta^t} \sum_{t=1}^{t=T} \sum_{u,k} f^t_{uk}(X^t, X^t_n, \eta^t)\eta^t_{uk}(1+E)^{-t} \tag{1}$$

under constraints:

$$S^t_p X^t = b^t; \tag{2}$$

$$X^t \geq 0; \tag{3}$$

$$\eta^t_{uk} = \left\{ \begin{array}{l} 1, \\ 0, \end{array} \right. \forall u, k, t; \tag{4}$$

$$\sum \eta^t_{uk} \leq 1 \;\; \forall u, t \tag{5}$$

$$X^t_u(1 - \sum_k \eta^t_{uk}) = 0 \;\; \forall u, t; \tag{6}$$

$$\sum_{t=\theta_1}^{t=\theta_2} \sum_{u,k} \nu^t_{juk}\eta^t_{uk} \leq R^{\theta_1,\theta_2}_j \;\; \forall j; \tag{7}$$

$$(\sum_k k\eta^t_{uk} - \sum_k k\eta^\tau_{uk})(t - \tau) \geq 0 \quad \forall k, u, t, \tau, \tag{8}$$

where
t, τ is current year index;
T is time horizon;
f^t_{uk} is nonlinear function of discounted cost at the $u-th$ component of the network given the $k-th$ level of its development (including development costs);
X^t is the sought for vector of network freight traffic intensity
X^t_n is the assigned vector of network passenger traffic intensity
b^t is the assigned vector of dispatch-destination volumes at the network nodes;
X^t_u is the sought for vector of loading of the $u-th$ component of the network;
$\eta^t = \| \eta^t_{uk} \|$ is the sought for vector of state (technical facility) of network components, and η^t_{uk} is the identifier indicating the $k-th$ state of the $u-th$ component of the network(if $\eta^t_{uk} = 1$ then it is there ; if $\eta^t_{uk} = 0$, then it is not available);
S^t_p is a generalized incidence matrix corresponding to inhomogeneous freight traffic

$$S_p = \| S_{ijl} \|, and \ \ l = 1, 2, ..., P;$$

$$S_{ijl} = \begin{cases} +1, & \text{if network arc } j \text{ starts at junction } i \text{ and } l \text{ type freight (altogether,} \\ & \text{there are } P \text{ types of cargoes) may be delivered by it;} \\ -1, & \text{if arc } j \text{ enters junction } i \text{ and it may deliver cargo } l \text{ ;} \\ 0, & \text{in all other cases.} \end{cases}$$

ν^t_{juk} is consumption of the $j-th$ resource by the $u-th$ component of the network for reducing it from initial to the -th state;

R^{θ_1,θ_2}_j constraint on the total consumption of the j-th resource within the period of time from θ_1 to one year θ_2 inclusive (generally, θ_1 is the starting, θ_2 final year of planning stage, most often five-year plan which is part of the planning period T; if constraint (7) is assigned separately for some year, then $\theta_1 = \theta_2 = \theta$.

Thus, according to objective function(1) the total discounted costs are minimized under three groups of constraints:

(a) technological: constraints (2) and (3) are a condition of accomplishing all transportations;

(b) on reconstructing processes: constraints (4)-(5)-each component may be only in one state, and in case the component is not created then the work it does equals zero-constraint (6); constraint(8) determines the observance of a hierarchy of states.

(c) on resource: constraint (7)-there is a quite definite amount of each resource.

Hence, solution of the problem(1)-(8) produces a list of activities aimed at optimal development of the network, activities schedule, and an optimal loading of all components of the network with different cargoes.

(1)-(8) is rather complex dynamic multiextremal problem solved by special mathematical methods based on successive optimization with respect to clusters of discrete and continuous variables and accounting for the problem specifics[7,12].

5. MODELING ROLLING STOCK REPRODUCTION

To simplify the model description, assume that there is only one type of rolling stock (vehicle) carrying one type of product. Assume also that the technical and economic indicators vary discretely, and for a certain period of time (year) each unit of the rolling stock operates in one mode, and then it instantly changes over to another state("ages"), hence, a new mode of operation may be assigned to it. The replenishment of the rolling stock with new vehicles and writing off aged units take place in the end of the year.

Designate:

τ = age of vehicle;

ν = mode of operation;

$N_{\tau t}$ = quantity of vehicles of τ years old operating in the $t-th$ year of the planning period;

$N_{\tau\nu t}$ = quantity of these vehicles operating in the $\nu - th$ mode. Each vehicle is characterized by performance $\Pi_{\nu\tau t}$;

$U_{\tau\nu i}$ = current costs (which, if necessary, may include repair or modernization costs);

$K_{\tau t}$ = reproduction cost

$\Lambda_{\tau t}$ = liquidation balance (price of scrap minus liquidation cost).

Then, proceeding from the above assumptions [11,13], the process of rolling stock reproduction may be described as follows:

$$\sum_{t\geq 1}\frac{K_{ot}N_{ot}}{(1+E)^{t-1}}+\sum_{t\geq 1}\sum_{\tau\geq 1}\sum_{\nu}\frac{U_{\tau\nu t}N_{\tau\nu t}}{(1+E)^{t}}-\sum\Lambda_{\tau 1}(N^{0}_{\tau-1}-N_{\tau 1})$$

$$-\sum_{t\geq 2}\sum_{\tau\geq 1}\frac{\Lambda_{\tau t}(N_{\tau-1,t-1}-N_{\tau t})}{(1+E)^{t-1}}\rightarrow min \qquad (9)$$

under constraints

$$\sum_{\tau\geq 0}\sum_{\nu}N_{\tau\nu t}\Pi_{\tau\nu t}\geq V_t, t\geq 1; \qquad (10)$$

$$\sum_{\nu}N_{\tau\nu t}=N_{\tau t},\quad t\geq 1,\quad \tau\geq 0 \qquad (11)$$

$$N_{\tau 1}\leq N^{0}_{\tau-1},\quad \tau\geq 1 \qquad (12)$$

$$N_{\tau t}\leq N_{\tau-1,t-1},\quad t\geq 2,\quad \tau\geq 1 \qquad (13)$$

where

V_t is a lanned requirement to be satisfied with the vehicles in year t;

N^0_τ is the number of vehicles of age τ, for t=0

k_{0t}, N_{0t} are price ad quantity of new vehicles in year t.

The economic content of relations (9)-(13) is as follows. The objective function (9) is the sum total of capital and current costs, discounted to year t=0,and subject to minimization (actually, the first and second summands) minus the sum obtained from liquidation of the written off vehicles for the entire reproduction period. Inequality (10) represents a requirement of complete satisfaction of demand for the product (transportation). The fact that the quantity of vehicles operating in different modes must be equal to the total number of vehicles of the given length of service is reflected in relation (11). The balance inequalities (12)-(13) testify to the fact that in the $t-th$ year the number of vehicles of age r cannot exceed that of age (r-1) in the preceding year (t-1) of the planning period.

Model (9)-(13) makes it possible to determine not only optimal structures of the rolling stock and its supply, but also the development rates of the sector manufacturing this type of vehicle to the measure to which the rates are determined by the dynamics of the volume of supply.

The dual problem to problem (9)-(13) has the following form:

$$\sum_{t\geq 1} \frac{Y_t V_t}{(1+E)^t} - \sum_{\tau} K_{\tau 1} N^0_{\tau-1} \to max \tag{14}$$

under constraints

$$Y_t \Pi_{\tau\nu t} \leq U_{\tau\nu t} + EK_{\tau t} + (K_{\tau t} - K_{\tau+1,t+1}); Y_t \geq 0; \quad S_{\tau t} \geq 0 \tag{15}$$

where

Y_t is dual variable to constraint (10)

$$K_{\tau t} = S_{\tau t} + \Lambda_{\tau t}$$

$S_{\tau t}$ is dual variable to constraints (12) and (13)

Variable Y_t in the given dual problem can be interpreted as an optimal value of product manufactured in the $t-th$ year, $K_{\tau t}$ as a full value of the vehicle of age in year τ, and $S_{\tau t}$ as an optimal value of the same vehicle in the considered sphere of its application.

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