Transportation, Problem-Solving and The Effective Use of Computers

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The argument of this paper rides on the conjunction of three themes: (a) the scope and complexity of transportation planning problems, (b) the structure of transportation planning as a problem-solving process, and (c) the development of highly flexible, multi-user, remote-access "interactive" computing systems. Analysis of the scope and complexity of transportation planning and of the problem-solving process leads to the conclusion that transportation planners need highly flexible systems with a variety of transportation planning tools. Analysis of the new computer systems shows how they will provide an environment for this required flexibility. Thus, our task is clear—to design and implement a flexible problem-solving system for transportation planning.

Brief examples are given to show specific system design implications of the argument presented.

•THREE streams of development have come together to create tremendous opportunities for fundamental changes in the process of transportation planning. This paper summarizes these three themes and explores their implications.

The first theme is the scope and complexity of transportation planning. It is developed through summarizing the policy options available, the wide range of their impacts, and the variety of models required for predicting the impacts of a given plan.

The second theme is the structure of transportation planning as a problem-solving process. Analysis of this structure indicates that the transportation planner must have available a variety of compatible models and procedures, and that he must have great flexibility in his use of these procedures in tackling problems of the complexity of transportation planning.

The third theme is the flexibility of the new computer systems, particularly the interactive, remote-access, multi-user ("time-sharing") systems. We conclude that this new technology will enable far more thorough analysis of problems as complex as transportation planning than has ever been achieved before, because these systems will allow the planner great flexibility in the conduct of his analyses.

Our task is to design and implement such highly flexible, problem-solving systems for transportation planning. This task can be accomplished successfully only through developing our understanding in each of these three areas—the scope and complexity of transportation planning problems, the structure of the problem-solving process, and the characteristics of the new computer systems.

In order to present clearly the main thrust of this argument, we must skim lightly over a number of highly complex and subtle issues. We consider this to be only an introductory statement—one which will be revised and expanded greatly as we gain knowledge and experience in the design of transportation planning systems.

Paper sponsored by Committee on Transportation System Evaluation and presented at the 45th Annual Meeting.

- FIXED FACILITIES (ALL MODES)
  - Networks--Configurations
  - Links--Locations
    - Capacities
    - Other operating characteristics
  - Nodes--Interchanges for single mode
    - Terminals for interchange between modes
    - Storage, parking, etc.
- VEHICLES (ALL MODES)
  - Quantities
  - Operating characteristics--Propulsion systems
    - Guidance and control systems
    - Relation between vehicles and supporting medium
    - Cargo- and passenger-carrying characteristics
- OPERATING POLICIES--Routing
  - Scheduling
  - Pricing (tariffs and tolls)
  - Segregation of traffic
  - Ownership
  - Regulation
- INFLUENCES ON DEMAND--Land-use controls
  - Advertising and merchandizing
  - Socio-economic development policies
  - Education
  - Enforcement

Figure 1. Transportation planning options.

SCOPE OF TRANSPORTATION PLANNING[1]

The scope of transportation planning can best be understood by enumerating (a) the types of policy options open to the planning agency, (b) the types of impacts of a plan which will affect the selection of a plan for implementation, and (c) the basic component models necessary for predicting plan performance.

The major policy options are summarized in Figure 1. The scope of this list is influenced strongly by the experience and insights gained by the highway engineering profession during the evolution of urban transportation planning over the last decade. In area after area, highway engineers have come to realize that highways cannot be planned separately from mass transportation facilities and parking; that pricing policies, such as tolls and parking charges, are potentially useful controls on demand; and that land-use controls and transportation policies must be carefully interrelated in order that land-use and travel patterns evolve in complement rather than in conflict.

Figure 2 summarizes the major kinds of impacts of transportation plans. Not all are equally important, nor even significant in every context; however, they are potentially relevant in every transportation planning analysis, and should be carefully evaluated before being classed as irrelevant in each specific context. Again, it is the history of urban transportation planning which stimulates the scope of this list, for we have long since learned that the first cost of the facility is only one of many possible impacts.

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[1] The discussion presented here draws strongly upon unpublished conclusions of the Boulder Conference on Transport Systems Analysis sponsored by the National Bureau of Standards in August 1964, under the direction of S. M. Breuning.

DOLLAR COSTS
- First Costs--Construction
  - Land Acquisition

- Continuing Costs--Maintenance
  - Administration and policing
  - Vehicle wear and tear

DOLLAR REVENUES--Tolls and other charges
- Special taxes

NON-DOLLAR COSTS
- Quantifiable--Travel time
  - Land takings--Recreation
    - Parking, etc.
  - Displacements--Population
    - Employment
    - Retail sales
  - Changes in growth patterns--Employment
    - Population
    - Land use

- Non-Quantifiable--Changes in social structure
  - Political power structure
  - Community structure
  - Disruption for individuals

  - Aesthetics--Driving experience
    - Perception of urban form

Figure 2. Impacts of transportation.

The relationships between the list of options and the list of impacts is shown in Figure 3. A transportation plan is defined in terms of the options; from this statement we wish to obtain a prediction of the impacts of the plan. To do this, we use one or more models—for example, traffic flow models and traffic assignment techniques to predict travel times and link volumes; land-use change models to predict the effect of travel time and other factors on land use; other models to predict construction quantities, land takings, and other data necessary for determining first costs.

A major part of transportation modeling is the prediction of the behavior of the transportation market. This behavior results from the interaction of supply and demand within the channels of the transportation network.

The physical facilities, consisting of networks, terminal facilities, and vehicles, "produce" transportation. The product—transportation—can be described potentially in terms of a number of variables (Fig. 4). We call these "level of service," or LOS, variables. The economists' notion of a "supply" function represents the production potential of a given set of transport facilities, as defined in terms of these LOS variables. For example, the supply function for a given highway link may indicate the dependence of travel time and/or travel cost on the volume of traffic using that road.

Similarly, a demand function can be defined. Such a function gives the volume of traffic desiring to use a given transportation facility as a function of the LOS variables; for example, traffic volume as a function of travel time and/or cost, as represented by the use of the gravity model with appropriate definition of the "distance friction" terms.

These considerations of the interaction of supply and demand in the transportation market (Fig. 3) lead to identification of a major type of model required for transportation analysis, the model for predicting the equilibrium between supply and demand in

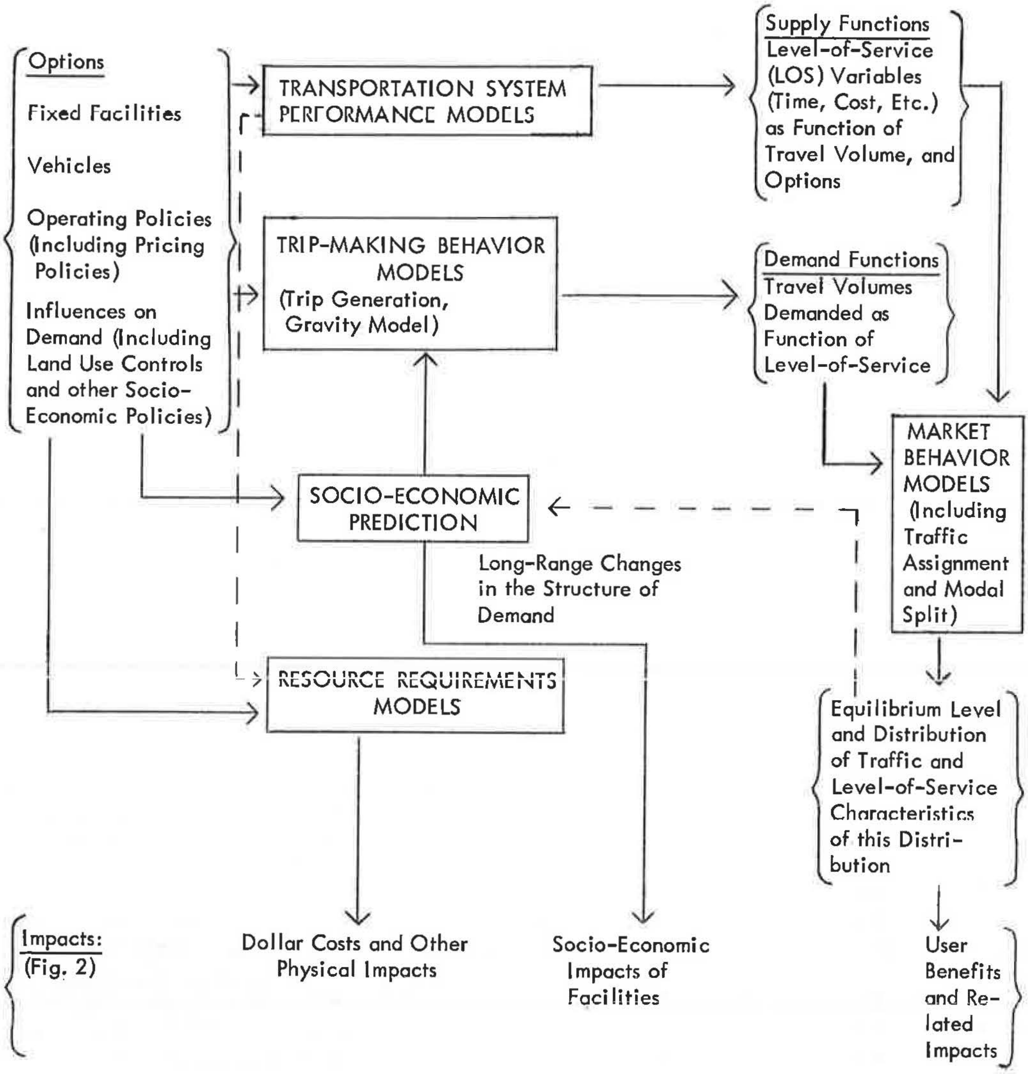

Figure 3. Major types of transportation models.

this peculiar market. This is the area in which urban transportation planning has focused much of its attention; e.g., assignment and distribution models. It is also a difficult area, as evidenced by the fact that there has not yet been developed a single, well-behaved, easily computed model for predicting this equilibrium.

The wide spectrum of transportation planning options, the wide spectrum of impacts to be considered, the large number of models required, and the difficulty of finding the equilibrium of the market all indicate the complexity of the transportation planning problem. This complexity is epitomized by the fact that we do not have a single, comprehensive procedure for determining the ideal transportation plan, but must go through a large number of steps with many, many recyclings. Thus, transportation planning is a complex problem-solving process, and must be studied as such.

TIME
- Total trip time
- Reliability--frequency distribution of trip times

COST (to user)
- Out-of-pocket (marginal) costs
- Continuing costs (e.g., auto ownership)

SAFETY
- Probability of fatality
- Probability distribution of accident types

COMFORT AND CONVENIENCE
- Physical comfort
- Psychological comfort
- Privacy

AESTHETIC SENSATIONS
- Sequence of visual impressions

Figure 4. Level-of-service variables.

STRUCTURE OF PROBLEM-SOLVING

The principles we will now discuss are not taken from profound psychological studies, nor are they derived from advanced mathematical specialties. Rather, they present an intuitive approach to establishing a fundamental understanding of the problem-solving process of engineering and planning, and are applicable as well to business decision-making and many other areas.

Problem-solving involves generating possible alternatives and selecting one for implementation. In the previous section we described the scope of transportation planning; alternative transportation plans are described in terms of the variables identified in Figure 1. We call these decision variables—the object of planning is to make decisions about the "values" to be taken by these variables. Alternative transportation plans will be examined in terms of their projected impacts (Fig. 2).

Alternatives and Search

The scope of transportation planning alternatives has been identified by listing the "decision variables." Each of these decision variables can take many different values; a transportation plan is described by identifying the corresponding value of each decision variable. The set of all possible combinations of values of the decision variables is the set of all possible transportation plans.

Some transportation decision variables are easily described, as continuous mathematical variables; however, most are not, for example, the configuration of a transportation network or the location of a particular highway. Most transportation decision variables are difficult to describe in any compact, neat way, so that the set of all possible transportation plans is also difficult to describe compactly.

The first phase of problem-solving is generating alternatives for consideration. We call the process of alternative generation "search" (Fig. 5). If the decision variables in transportation were continuous variables, generating alternatives might be significantly easier. But the decision variables are so complex, and the set of possible transportation plans in a given context so large, that search is difficult and takes measurable effort.

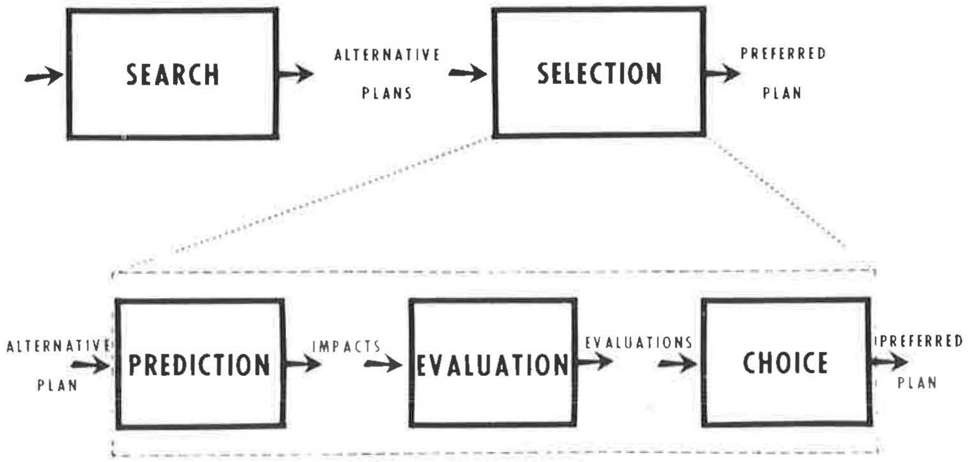

Figure 5. Basic problem-solving modules.

Goals, Impacts, and Selection

Transportation plans are implemented to achieve goals (we ignore here the questions of whose goals, or which goals). The basis for choosing one plan over another is the judgment as to which plan will most likely achieve the goals.

We call the process of examining plans in terms of their achievement of the goals "selection." We identify three major phases in selection. "Prediction," the first phase, operates on the description of a plan in terms of the decision variables to predict the plan's impact. These included physical and socio-economic impacts (Fig. 2). Note that costs and value judgments are not attached yet; prediction is concerned with purely real-world questions. The second phase, "evaluation," involves placing values (dollars and others) on the impacts through costing and other techniques. For example, determination of the effect of a plan on travel time is prediction; the changed time is an impact. Placing a value on travel time and then computing the total dollar value of the changed travel time is evaluation.

The third and final phase of selection is "choice." In this phase, the values of the impacts of alternative plans are compared, and a choice made. In those plan analyses where all values are in a single common unit, such as dollars, choice is not difficult. However, in most situations dollars must be weighed against such factors as loss of recreation land, loss of tax base, destruction of neighborhood social structure, and others; in such cases, choice is indeed difficult. Clearly, trying to reduce everything to dollar values will not answer the difficulty.

Implications of Search and Selection

Examining the discussion of the scope of transportation with which we began, we reach several conclusions:

1. The models identified in Figure 3 address only the prediction problem in selection. In addition to these prediction models, we need techniques and models for assisting the transportation planner in evaluation and in choice.
2. Evaluation models would consist primarily of cost models, but will often require heavy planner judgments as inputs, especially for evaluation of non-dollar-valued impacts.
3. Choice requires balancing dollar-valued costs and benefits against evaluations of non-dollar-valued impacts; for example, dollars of construction cost against removal of a popular park. Therefore, except when the difficulty of choice is assumed away through use of dollars or another denominator, choice procedures will require heavy planner interaction.

4. Besides selection models, the planner could use methods to aid in his search, or generation of alternative transportation plans. Such techniques might be optimizing algorithms, or just rule-of-thumb heuristics. Linear programming would be an example of the former when used to select link sizes (number of lanes and capacity) for a given network configuration. An example of a heuristic would be a procedure which, given a network proposed by a planner and already evaluated, would generate other networks by making small changes in the original one. A third kind of approach, guiding the planner's creativity in an organized way, is represented by the method of Alexander (1).

5. The full range of decision variables and of impact types is very large; even the crude decomposition of the plan analysis process shown in Figure 3 results in several basic models. In actuality, the planner must use a very large number of detailed models—trip generation, modal split, traffic assignment, earthwork computation, bridge cost estimation, vehicle simulation, land-use prediction, population prediction, and many others—to span from the full set of decision variables to the full set of impact types. Transportation planners cannot expect to develop a single comprehensive model which can be "solved" to determine the "optimal" plan.

6. The planner does not yet have tools for determining analytically the equilibrium in the transportation market between the supply and demand functions, for many reasons—the large number of significant level-of-service variables, the geographical distribution of demand, the different demand functions of different socio-economic groups, the different supply functions of different transport modes, the feedback relationship of pricing policy options, and, most important of all, the interaction of supply and demand in the constrained channels of the transportation network. Therefore, determining the equilibrium distribution of traffic in a network requires a series of interacting computational approximations (use of trip generation, trip distribution, modal split, and assignment models). Of course, taking into account such long-range shifts in the demand functions as correspond to land-use changes is even more difficult.

The implications we derive from this discussion are that there are many different tools needed by the planner for resolving transportation planning problems—a variety of search procedures, a variety of models for prediction of impacts, and a variety of procedures for guiding him in evaluation and choice. Further, it is not likely that the particular bundle of tools applicable to a problem will stay constant, nor that the sequence of their application will be fixed and known a priori. Therefore, the planner requires that all these tools be available to him, within the same computer system, with great flexibility provided for him to use his tools whenever and in whatever sequence he desires; the planner's decision as to what to do next, and with which tool, must depend on the results of his preceding analyses.

Further Implications

Space prevents us from going into a discussion of many other aspects of the problem-solving structure of transportation planning. We summarize some of the more significant:

1. Sensitivity analysis—the planner is often uncertain about the true value of many elements entering into his analysis (for example, predicted increase in income or in auto ownership). The planner needs tools for explicit analyses of the sensitivity of his choices to variations in the assumed values of key data.

2. Uncertainty analysis—having determined the sensitivity of his decisions to key factors, the planner may wish to use choice procedures which incorporate uncertainty explicitly—either probabilistically (perhaps with Monte Carlo techniques) or through decision rules (3, Chapter 13).

3. Analysis of data base—for example, parameters of travel behavior models (generation rates, mode choice functions) are inferred statistically from large volumes of collected data. The planner needs statistical analysis tools to enable him to go back occasionally to the raw data for refinement or revision of earlier estimates, or for analysis from an alternative approach.

4. Hierarchical structure—the planner naturally deals not only with detailed alternatives (transportation plans as defined in Fig. 1), but also with broad, aggregated alternatives, such as radial versus grid systems. The planner needs procedures for deciding when he should be operating at detailed levels and when at broad levels (see Manheim, 6).

5. In such large and complex problems as transportation planning, the planner's view of the problem will change as the process evolves. The goals will change, and other emphases will evolve. The planner will need tools for reevaluating earlier choices, for revising his models to reflect goal changes, etc.

6. Often the planner will need to construct new types of models and validate them against the data base (so long as still within the range of behavior incorporated in the data).

NEW COMPUTER SYSTEMS

Third-generation computer systems will be highly flexible. This will be most typified by the time-sharing models which will provide a large number of users remote access to substantial computer power on an as-needed basis.

From the point of view of the user, time-sharing means that he can have access to the computer through his own console, which may be as simple as an electric typewriter and may be remote from the computer, in the user's own office. From this console the user can enter data, run programs, receive output, and modify, compile, and debug his programs. He has the computing speed and memory capacity of a large portion of the computer available to him, but because he is sharing these facilities with other remote users, the cost is significantly less than the full cost of the computer. Time-sharing systems make available immense computing power for use in small or large chunks as the planner needs it, delivered wherever it is most convenient to him.

Third-generation computers will have another major source of flexibility in the software capabilities available. These capabilities are illustrated by those incorporated in ICES (Integrated Civil Engineering System), a prototype operational system now being developed by the Civil Engineering Systems Laboratory at the Massachusetts Institute of Technology (6, 7).

One of the most important characteristics of ICES is its capability for providing problem-oriented, command-structured languages for various application areas such as structural design, surveying, transportation planning, and highway design. With these languages, the engineer is able to express his processing requirements through sequences of commands. These sequences are highly variable; the engineer can vary not only which specific computational steps he uses in analyzing his problem, but also the order in which they are executed. Other capabilities in ICES, such as dynamic memory allocation, data-base management procedures, and list-processing features, add to the flexibility of the system.

IMPLICATIONS

Through provision of highly interactive processing access via time-sharing and with flexible software, the third-generation computer systems will provide great flexibility to the planner. They will allow him frequent and continuous interaction with his programmed procedures and his data base; he will have freedom to choose the tools to use and the sequence in which they are used.

The planner can consider his models and procedures as a collection of problem-solving modules; he executes one module, observes the results, and selects a module to execute next. This process is repeated until a preferred plan is achieved.

Some modules will be search procedures, others prediction models, still others will assist him in choice. Some modules will deal with traffic, others with land use, social structure, or construction estimates. No single module is itself sufficiently powerful to be used to solve a transportation planning problem in its entirety; the planner must ultimately use a large number of these modules, though not necessarily all of them.

To summarize, then, we see that the conjunction of these three themes implies definite objectives for system design. Because of the scope and complexity of the transportation planning problem, we must make available a variety of specific predictive models. Furthermore, we must recognize explicitly that transportation planning is a problem-solving process, so that we must provide modules not only for prediction, but also for search, evaluation, and choice, as well as a variety of other support roles (e.g., sensitivity analysis, hierarchical structure, systems analysis). Finally, it is only because of the new hardware-software technologies that we can actually implement a system with such capabilities.

This kind of flexible problem-solving system for transportation planning must be our objective.

EXAMPLES

To illustrate these ideas and stimulate discussion, we show some relatively simple examples. These are presented as pairs of interacting analyses. The planner will move back and forth between each type of analysis, or procedure, in the pair.

Network Generation (Search) ⟷ Network Selection

Assisted by computer procedures, the planner generates a network. Next, he utilizes other procedures to predict and evaluate network impacts, and to compare the network with others previously examined. Then he generates and examines a new network or modification of the old. Thus, he uses search and selection procedures in alternation.

Free Assignment ⟷ Capacity Constraint Assignment

The planner will make "free" or unconstrained assignments to determine major desire patterns. As a guide to network generation, he will then use capacity-constrained assignments to determined the deficiencies in the existing or planned network. The differences between the two assignments will indicate in a general way the effectiveness of the network. Making small changes in the network, he will go back again to free assignment, repeating the cycle.

Network ⟷ Link

Having generated and examined a number of alternative networks, the planner fixes upon the preferred network. With this as a basic plan, he generates and examines alternative locations for one or more specific links in the network. If at some point the most preferred link is significantly different in its effect on the network (on flow pattern, user costs, land-use impacts, etc.) from that assumed in making the network choice, the planner must return to the higher level network problem and revise his selection at that level, perhaps generating new alternatives. (This is a two-level example of hierarchical structure.)

Land Use + Network ⟷ Network

Because of the feedback effect of transportation on land use, in general the planner can evaluate networks adequately only with the aid of land-use prediction models. However, once having analyzed the interaction of a network with land-use changes, the planner may be able to assume that for small changes in the network the land-use evolution is approximately the same. So long as this applies, he need only use network flow models (e.g., assignment), and does not need to do land-use prediction for each new network; but as soon as the networks become significantly different, he must use both land-use and traffic models again.

Regional Product and Income Distribution ⟷ Total Annual Costs

Since transportation exists only to serve the region, evaluation of transportation plans requires prediction of their effects on total regional product and regional income distribution. However, when regional parameters are not sensitive to small differences in plans, total annual costs of the networks (first + user + continuing costs) are adequate as proxies for the regional measures. Thus the planner will sometimes use the regional growth and income models and other times use only direct cost models.

Quantitative (dollar) Criterion ⟷ Choice Mechanism

For many alternative plans, the non-dollar-valued impacts may be sufficiently similar or sufficiently obvious in their implications for choice that use of a single-dollar criterion to measure the desirabilities of alternative plans is acceptable. For others, however, choice may be extremely difficult and require analysis of the relative liabilities and benefits of each scheme. Then the planner will use various models to help him explore his judgments (perhaps scale construction methods, or even procedures for guiding introspection in the development of dollar or other equivalents of non-dollar impacts).

CONCLUSION

At this stage, the general argument of this paper is largely philosophical. Final judgment as to relevance and significance can only be made after its implications have been shown in the design of a specific set of computer-assisted transportation planning tools. Therefore, we ask that this paper be considered an opening statement, a statement of intent. In the future, we hope to show in detail the way this argument has influenced our design of transportation planning systems.

ACKNOWLEDGMENTS

While all responsibility for the statements herein lies with the author, the following individuals have been major stimulants to the development of the ideas presented: Professors C. L. Miller, P. O. Roberts, and S. M. Breuning of M. I. T., and A. Scheffer Lang, Department of Commerce.

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