THE TRANSPORTATION LABORATORY: TEACHING FUNDAMENTAL CONCEPTS OF TRANSPORTATION SYSTEMS ANALYSIS

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Development of an undergraduate transportation laboratory is under way as a mechanism for teaching transportation systems analysis at the undergraduate level. The transportation laboratory is in the form of (a) a workbook of exercises in transportation systems analysis and (b) an integrated set of computer programs and data for executing the exercises. The computer programs have been developed by additions to the DODOTRANS problem-oriented computer language. Each exercise teaches the use of a particular laboratory capability, develops an understanding of a specific aspect of transportation systems analysis, and poses questions for the student to explore in his own way, by using the laboratory. Emphasis has been placed on developing an understanding of the interrelationships between transportation technology and social impacts in the context of multimodal transportation systems.

•FROM THE VIEWPOINTS of both teaching and research, experiments in the socioeconomic arena (urban problems, transportation, etc.) are difficult to perform. In the physical sciences, the student can often isolate a piece of the real world in the laboratory in order to experiment with it. In transportation, however, experiments with the real-world system are very difficult to perform because they are expensive and time-consuming, and, most important of all, they have profound social, economic, and political effects. Yet, from the viewpoint of education, it is highly desirable to provide "laboratory" experience for students in transportation. Such a laboratory experience can

1. Give the student an intuitive, deeply felt perception of the interactions among the components of the transportation system and between the transportation system and its socioeconomic context;
2. Encourage the student to experiment (in the laboratory) in an exploratory, natural way with a wide range of transportation and regional development policy alternatives; and
3. Motivate the student to take more highly specialized courses in transportation techniques (e.g., demand analysis, network flow models, transportation technology, and sampling design).

To achieve this kind of laboratory experience, we can make use of the computer. In the computer, we can construct a simulation of the real-world transportation system and its interactions with its environment. Even if the student cannot easily experiment with the actual transportation system, he can experiment with the simulation. Thus the computer becomes our "transportation laboratory."

BASIC OBJECTIVES

Our basic objectives in developing this transportation laboratory have been

1. To teach the fundamental concepts of transportation systems analysis in a way that transcends the properties of particular models or techniques;

2. To develop in the student an understanding of how to go about analyzing problems systematically, whether they be transportation or nontransportation problems, with particular emphasis on how to structure the systematic analysis of a problem in which a complex simulation model will be used (such as a transportation network analysis package); and

3. To demonstrate for the student the interrelationship between technological and social choice issues by illustrating how decisions about technological alternatives—in this case, transportation alternatives—have profound sociopolitical impacts and consequences and by showing him how such decisions with social consequences can be analyzed systematically.

In a sense, the most fundamental objective of all is to give students a basic introduction to the interrelationship between technological and societal problems, in general, and to urban transportation problems in particular, in a way that also develops an understanding of how to go about analyzing such problems. Thus, the basic transportation laboratory course is an introductory course. There are no prerequisite courses, and our target audience is freshmen and sophomores. From this basis, students will go on to take more advanced courses in a variety of areas, including transportation and mathematical modeling techniques. There is a parallel graduate version of this course that is more technique-oriented and that makes less use of a computer laboratory.

In a sense, what we are trying to do is to challenge those students who are concerned about the problems of contemporary society, have a quantitative and analytical orientation (as most of the students at M.I.T. do), and are looking around and groping for a role in which they can operate professionally to work on such problems. Thus, our objectives are not only to teach transportation but also to challenge students in a more general way to deal with the problems of society.

THE LABORATORY CONCEPT

To function effectively such a laboratory must contain models, computer programs that simulate the behavior of transportation systems and the interactions between transportation and its environment; and data, representing real or hypothesized urban or megalopolitan regions and their transportation systems. For example, there would be models for simulating traffic flows over highway and transit networks in a particular metropolitan area and data for calibrating these models.

To use the laboratory effectively as a teaching environment, the following must also be provided:

1. Instructions on how to use the laboratory—how to set up and run various types of experiments; and
2. A series of carefully designed experiments.

In our development of the laboratory, we have integrated both of these components.

Our objective is a series of laboratory exercises, in each of which the following elements are integrated:

1. A basic concept of transportation systems analysis is introduced;
2. Simple examples are given;
3. Simple exercises are given to reinforce and test the student's understanding of the concepts—simple enough so that the problems can be solved without the use of a computer, generally graphically or by simple algebra;
4. The relevant computer capabilities [for example, specific DODOTRANS (3) commands and routines] are introduced and demonstrated by examples;
5. The student uses computer routines to solve a "structured" problem, that is, one for which there are "correct" answers (this tests his understanding of the basic transportation systems concept and his ability to apply it, both with and without the computer); and
6. The student is then given an unstructured problem in which he must exercise judgment in formulating the problem and in his analysis of it.

This description should indicate that the use of the computer is a means, not an end in itself. The DODOTRANS language is a problem-oriented computer language that is very easy to learn in the context of developing an understanding of transportation problems. To use this language, the student does not have to learn computer programming in the usual sense, as is the case with FORTRAN or other programming languages. He only has to learn how to write a description of his transportation systems problem in the relatively simple DODOTRANS commands. (We have found that students with little or no prior computer experience can master both the transportation systems concepts and the use of DODOTRANS in 4 to 6 weeks.)

For example, an exercise in the comparative analysis of urban transportation technologies might take this form: Given the data, set up and do a comparison of the cost and service characteristics of rail transit and highway in a particular urban corridor. This part of the exercise would teach use of the appropriate laboratory techniques (computer programs in the form of problem-oriented language commands), as well as provide an understanding of the relative advantages of the two modes under various conditions of demand and assumptions of cost. Develop data for some other existing or projected modes, and compare them with previous results. This would stimulate the student to think about the basic similarities and differences among transport modes. Propose some desirable objectives for a new mode to meet; suggest the form such a mode might take. This challenges the student to think about the fundamental characteristics of different possible new modes and to do analysis to compare the cost and service performance of a possible new mode with the modes analyzed previously.

BASIC TRANSPORTATION CONCEPTS

It is useful to review briefly the basic concepts of transportation systems analysis that we are trying to teach.

First of all, we begin from the perspective of analyzing transportation systems as integrated, multimodal systems, in which we consider as a single system all the transportation facilities of a region. We analyze this system as a whole, considering all components of the system, and treat flows from initial origin to final destination (2). There are a wide variety of options open to the transportation analyst, ranging from choice of technology and characteristics of particular technologies, network configurations, link characteristics, the number and characteristics of vehicles, and the way the vehicles are routed and scheduled through the system to the prices that are charged and other aspects of operating policies. The impacts to be considered in a transportation analysis are many: the impacts on users, with careful differentiation of the impact on different groups of users; the impacts on the operators of the various transport facilities; the functional impact of transportation, through affecting the spatial organization of social and economic activity and the time pattern of the development of a region; the "physical" impact caused by the mere presence of transportation facilities, such as air pollution, noise pollution, visual blight, land taking, and displacements of families and jobs; and the impacts on various levels of government, through changes of tax revenues, subsidies, and the like.

The basic framework of analysis of transportation alternatives is that arising from the concept of equilibrium within the transportation network. This requires that the transport system be modeled as a network with supply functions for various links in the network (links include line-haul links as well as terminals and other transport facilities) and that demand functions be developed for all the actual and potential users of transportation. The core of the problem of predicting the impacts of a particular transportation plan or policy is the prediction of the flows in the network, based on the equilibrium between supply and demand. In practice, this requires use of a complex system of models (2).

Finally, it must be recognized that the system of models used for prediction is only the first step. To actually perform transportation systems analysis requires search procedures to develop transportation and development alternatives that are worth testing in the simulation model system. In addition, evaluation and choice procedures required through alternative transportation plans can be prepared, and conclusions can be reached on the relative desirability of the several alternatives analyzed.

These ideas about the basic concepts of transportation systems analysis led to the design of the following series of concepts to be covered in a semester of approximately 15 weeks:

1. Supply-demand equilibrium over a single link—Hand and computer calculations of equilibrium are performed on a simple link connecting two points, which explores a range of demand parameters and link alternatives.
2. Supply-demand equilibrium in simple networks—Equilibrium flow patterns in various simple networks are explored to develop an understanding of how flows in networks are distributed.
3. Alternative flow distribution rules—Simple networks are used to explore different assumptions about the behavioral basis of flow distribution, by comparing such approaches as the so-called "behavioral traffic assignment" with "normative optimization."
4. Demand functions—Alternative values of demand parameters and forms of demand functions are tested against data, and experiments are made with various calibration techniques. The "best" demand models and parameter values are then used in an analysis of a simple network, and the results for different demand functions and parameter values are compared.
5. Technology—Simple models of transportation technologies (e.g., rail transit, highways, dial-a-bus, dual mode, air) are used to develop and explore significant trade-off relationships within and between modes. For example, total cost, average cost, and marginal total cost curves would be derived for different modes, for different levels of user service.
6. Network patterns—For several types of distributions of development patterns in a region and given a list of the available technologies that could be used, the student tests different network patterns to develop an understanding of how the effects of networks and alternative land use and economic policies are interrelated. For example, a student might test several transportation networks ranging from highway-dominated to transit-dominated to a system with innovative transportation technologies, each against several alternative land use patterns for metropolitan regions.
7. Differential impacts and substitutability of options—This is perhaps one of the most important blocks of exercises. The student explores a wide variety of alternatives and develops an understanding of what it means to systematically explore options and to trace out the differential impacts on various groups. For example, a student might work with an urban transit and highway corridor and vary rapid transit station spacing, the choice of line-haul transit technology, the train frequency, the choice of feeder service, automobile parking fare, automobile parking capacity, and other policy options. He then might trace out the differential incidence of costs and benefits as the options are varied.
8. Time staging of transport investment—This exercise will develop an understanding of the sequence of steps involved in implementing, in an evolutionary way, major transportation systems changes. The student evaluates the alternative time-staged sequences of transport investment and explores uncertainty about characteristics of demand and technology.
9. Case problems—In one or more case problems, for a period of several weeks each, at the end of the semester, the student does a comprehensive analysis of a single transportation problem. He assembles the necessary data, constructs supply and demand functions, designs alternative transportation plans, tests them, and analyzes the socioeconomic impacts on different groups by systematically exploring the options and finally reaching a decision on a system to recommend. The student writes up his recommendation, including documentation of his analysis.

This sequence of exercises is a projected target. It is quite likely that this will be too many concepts to try to get across within a single semester. At present, many of these concepts have been incorporated in the exercises developed to date. Before describing these exercises, however, it is useful to amplify what we hope to teach in terms of concepts about systematic analysis.

SYSTEMATIC ANALYSIS IN TRANSPORTATION

There are two major themes in our image of systematic analysis. It is often useful to describe these in terms of hypotheses. First is the calibration problem. The issue here is what models and parameter values for a particular model are most likely to simulate the real world. This is the typical thrust of "hypothesis testing" in transportation analysis: Alternative model forms and sets of parameter values are formulated as hypotheses that are then tested against the data. Various statistical tests are used to measure goodness of fit to determine the most appropriate model forms and parameter values to be used. Exercises to explore this kind of problem would stress the hypothesis-testing aspects of calibration of demand models, calibration of networks, and the like and would involve developing some elementary notions of statistics.

Second is the decision problem. Once a model is calibrated, the problem then is to use the model to analyze the decision issues, based on the assumption that the calibrated model is a reasonably valid picture of the real-world system. In this kind of analysis, the basic hypotheses concern the following:

1. What are the possible actions open to the transportation decision-maker?
2. What are the anticipated consequences of the various actions?
3. What are the key decision issues, what are the technological trade-offs open as possible options to the decision-maker, what value trade-offs are involved in making the choice, and what value judgments are required to reach a decision?

This too can be viewed as a hypothesis-formulation and -testing problem. Here, instead of hypotheses about models and parameters of models, the hypotheses are about actions and their consequences and about which actions are most desirable. The "experiments" to be conducted are the simulation model, to predict flows and other impacts in a transportation system. The approach to analysis must reflect this hypothesis-testing view: Based on the results of several preceding analyses, the transportation analyst formulates a set of hypotheses about what desirable actions might be like, what their impacts would be, and what decision issues these would illuminate; to test these hypotheses, he formulates one or several runs of the transportation model system and, then, based on the results of these model runs, revises his hypotheses.

Thus, the simulation model in the transportation laboratory is used much as a piece of "physical" laboratory equipment, and an attitude of "experiment" design is appropriate. There is a basic mode of formulating and testing hypotheses, which is essential in transportation systems analysis. Our objective is to develop exercises through which the student develops a feel not only for the hypothesis formulation and testing aspects of model calibration but also for the hypothesis-formulation and -testing aspects of exploring possible actions to be implemented in the real world.

THE PRESENT COURSE

We now turn from philosophical issues and general approach to indicate precisely where we stand in the development of this teaching material. These concepts have been evolving over several years, most especially in the context of a graduate course, 1.201 Transportation Systems Analysis I. This course has been the basic introductory course for entering graduate students and advanced undergraduate students and precedes a sequence of several more advanced transportation systems courses. The basic concepts outlined here were first implemented in teaching this graduate course in the fall of 1969, in a rudimentary way. In spring of 1970, a small experimental version of the undergraduate form of this course, 1.20 Transportation Laboratory, was conducted as a pilot experiment, and enrollment was restricted to 10 students. Since then, the course has been taught on a regular basis in the fall term and also in spring of 1971. Enrollment has been steadily increasing and is now 25 to 30 students.

In this course, the full flavor of the laboratory concept is explored. The experiments were initially structured into three major sections:

1. Basic concepts and techniques,
2. Project I—urban transportation corridor, and
3. Project II—airport access.

In section I, the emphasis is on developing an initial understanding of concepts and techniques: basic notions of supply, demand, equilibrium, network flows, and the like. Then, additional concepts and techniques are developed in the context of two major projects or case studies. For example, project I deals with the problem of highway and transit complementarity in an urban corridor (suburbs to central business district) using the southeast corridor of the Boston region as a case study. Concepts of multimodal demand models, substitutability of pricing and operational improvements for construction of new facilities, and exploration of new urban transportation technologies are included. Particular emphasis was placed on the differential tracing out of impacts by dividing trip-makers into two income groups as well as into radial rings of residence locations. The second project deals with access to airports and choice of access mode in an urban region. The specific exercises that have been developed are discussed below.

Part I: Basic Concepts and Techniques

Exercise 1—This first exercise introduces the basic concepts of transportation systems analysis, building around the concept of equilibrium analysis. The emphasis is on simple one-link networks, with linear supply and demand functions. Simple manual computations are included to reinforce the concepts. Then, the use of the computer for the analysis of such networks is outlined, including extracts from sample computer runs and introduction to some of the basic DODOTRANS commands. There are also explorations of how changes in the parameters of the demand functions would affect the predicted results, which demonstrates, among other things, the shift of demand over time due to population growth and income change. The exercise concludes with a simple comparison of alternatives for replacing a particular hypothetical highway link. Students also code and punch simple DODOTRANS runs, which are checked for basic understanding of concepts and DODOTRANS commands.

Exercise 2—This exercise introduces the complexities of multimodal network analysis. There is detailed instruction in the use of DODOTRANS commands for setting up and executing a multimodal network analysis. A simple case study deals with a multimodal network with three modes, highway, transit, and park-ride, for a single origin-destination pair. The student analyzes various alternatives by using listings of computer runs that have been prepared for him. Through the use of listings of runs, the basic concepts of transportation systems analysis and of the use of the DODOTRANS language can be reinforced and understanding of details can be tested, without the time lag and expense of each student's actually preparing and executing computer runs. For the last part of the exercise, students code up and run their own alternatives. In studying this simple network, students explore various alternatives that emphasize the substitutability of fare, service, and other options for the construction of transit and/or highway line-haul or terminal facilities. As an example of the approach, the following sequence of classes is held:

1. Class 1—Here is a network with predicted flows for future year X. Class discussion: Where are the "bottlenecks" or other problem areas? Why have they come about?
2. Class 2—Here is a list of possible improvements to the network (including pricing and service changes as well as the construction of new links such as expressway or parking facilities). Discussion: What effects do you think each of these possible improvements would have? Why do you think they would have these effects? Can you explain them in terms of the theoretical concepts and of the particular numerical values of parameters, such as the parameters of the demand functions? What other alternative improvements should be examined?
3. Class 3—Here are tables showing the impacts predicted by the computer for each of the alternative improvements. Discussion: Can you expect these to occur in the real world? For a different set of parameters (several are specified), how would you expect the results to be different? Why?

By the end of this block of exercises, the students know how to set up and execute a multimodal transportation systems analysis using DODOTRANS, and they have an understanding of the basic concepts of network equilibrium analysis and of the detailed commands necessary to use. This set of exercises takes about 6 weeks.

Exercise 3 deals with the calibration problem, with a concentration on demand model calibration. Basic concepts of linear and product forms of demand models and of elasticity and cross elasticities are introduced, as well as identification and other aspects of the demand model calibration problem. Simple hand-calculated exercises are used to reinforce these concepts.

Parts II and III: Projects

Exercise 4 is the first case study, The Urban Transportation Corridor, based on the southeast corridor of the Boston metropolitan area. Two modes are modeled, highway and transit; the metropolitan corridor is divided into five suburban rings and a CBD, with two groups of travelers, high income and low income. Each group has different demand functions, represented by different parameters of a single demand model. The case study has been made as realistic as possible by using the available data for this corridor to the maximum extent feasible. The students explore a wide variety of alternatives. The first several groups of explorations are in response to structured questions: The class is asked to look at the results of computer runs in which transit fares and other characteristics of the system were varied over several different levels. Each student traces out the differential impacts of these alternatives on different groups, not only from the perspective of the operators of each mode but also in terms of the ridership from different rings and different income groups. To reinforce and expand his understanding of these differential impacts, he summarizes the various runs in terms of trade-offs between the net revenue to transit and highway operators and user benefits represented by travel time, fare, and other measures (including a consumer surplus measure). At the end of this exercise, he is given the assignment of formulating his own alternatives:

"You are now on your own. Develop and study alternative solutions for the southeast corridor: (a) Develop one or more alternatives that you think will be desirable. (b) First, write down your hypotheses about what you think the consequences of those alternatives would be. (c) Then decide which ones are worth testing in detail. Write down your reasons why. (d) Set up and execute one or more runs to test your hypotheses. (e) Review your results and repeat previous steps if desirable and if there is time and computer budget left. (f) Prepare a report on the results:

1. Summarize (no more than two pages) the key choice issues. Which alternatives are most important to consider; what are the key issues in choosing among them (the trade-offs) and your recommendations?
2. Document your analysis process, including the results of the various steps above."

Exercise 5 is the second case study, an airport access problem. Whereas in exercise 4 a number of very structured questions are asked, leading the students step-by-step through a systematic analysis of the alternatives, exercise 5 is open-ended and concentrates on the design of an analysis process that will lead to answers to the problems caused by ground travel to and from airports. The student is asked, "What would you do, given a range of available amounts of time and money?"

EVALUATION

In the process of offering the urban transportation laboratory course a number of times, we have made a number of operational improvements, so that now we feel we have a working, tested course with which to introduce undergraduates to transportation systems analysis. To date, we have made the following major changes and elaborations. Although we did not do so when the course was first given, we now stress the need to prepare good, written engineering reports to summarize the work done on the various case studies. This stress has resulted in not only better reports but also better analysis by the students. Also, a role-playing game concerned with the problem of airport expansion has been developed. This was first used in spring of 1971. The students have expressed great interest in the game, stating that it helps them to see the role of transportation analysis in the real world.

More generally, a number of significant conclusions about the course and the approach as a whole have been reached.

In terms of achieving the basic objective of student involvement, the students seem to be highly involved and committed to the course each time it is taught. Several students have been instrumental in having their friends enroll in following terms. A number of students have shown their continued interest in transportation by taking advanced courses, by working as student assistants on transportation research projects, and by earning academic credit while helping to conduct the course as undergraduate teaching assistants.

Each time the course is given, the students are asked to complete a course evaluation questionnaire. These questionnaires indicate that the major attraction of the course is its relevance, combined with the analytic computer aspects: They can see the relevance to everyday transportation problems with which they are familiar (one sophomore from Long Island sees the problem that his father faces everyday in commuting to Manhattan in one exercise), and they can also see the role that systems techniques (computers, economic analysis, and the like) will play in dealing with these problems. The students also have expressed satisfaction with the case study approach, although they would prefer more and shorter studies. Many have felt that a previous economics course would have been helpful as preparation for the course.

The second major conclusion is that the development of these kinds of exercises is not simple. Data must be gathered from actual transportation studies where available; these data are difficult to find and often inconsistent and must be extracted and adjusted carefully. The theoretical concepts of transportation systems analysis must be clearly worked out, and it is surprising how much is learned by constructing simple examples for hand calculation. Several computer examples must be developed to bring out the basic issues and teach the uses of specific computer language commands. Then, this must all be integrated with a case study project. The development of carefully structured exercises, together with a series of open-ended questions, which require the student to formulate his own experiments, takes very careful thought and planning.

Third, and finally, one very important conclusion is that we, the faculty and staff involved in teaching the course, are learning a great deal from it, perhaps more than any of the students. In trying to structure and formalize the concepts of transportation systems analysis and to develop well-integrated exercises, we are forced to rethink and clarify a lot of things we have assumed as givens. Particularly important here is the way we and our students are learning to treat the computer, as a tool for policy analysis. We stress a continual comparison of computer results against theoretical and intuitive judgment, as for example the series of class discussions in exercise 2 and the discussion of hypothesis testing. We stress using the computer model as a tool to analyze policy questions, not as an end in itself. We place great emphasis on exploring the social, political, and environmental choices that must be addressed. We expect to learn a great deal from our students in constructing these exercises and have learned a lot already.

FUTURE PLANS

We are continuing development and refinement of this transportation laboratory course. The exercises described have been documented and are available for limited distribution. We hope to begin circulating these to get comments and criticisms from our colleagues in practice and in academic institutions. We look forward greatly to widespread participation in this experiment, and, as soon as it is feasible, we will attempt to make these exercises and computer programs available to other institutions.

Major directions of future work are

1. Development of exercises for problem contexts other than those that have already been developed,

2. Incorporation in the exercises of quantitative and qualitative aspects of social and environmental impacts of transportation alternatives,

3. Expansion of DODOTRANS capabilities to include representative forms of the conventional urban transportation planning model system,

4. Continued revision of previously developed material to promote better teaching effectiveness, and

5. Experiments in presentation approaches in order to reduce computer expenditures required per student.

We live in an exciting period in the field of transportation. The research problems are challenging. The problems of teaching transportation effectively are even more challenging. The "transportation laboratory" concept that we have described is one possible approach to teaching transportation systems analysis effectively.

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