Computers and Engineering Economic Analysis

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•THIS PAPER describes, in summary fashion, the principal characteristics of advanced engineering computer systems, how these systems can contribute to improved engineering design and economic analysis, and some general engineering analysis methods that require computers for solutions. Much of the material contained in this paper is based on earlier publications (7, 13). The purpose is to communicate an idea of the kinds of engineering capabilities that are just now coming into actual practice and of the direction that developments will likely take. The discussion is oriented primarily to the problem of highway location and design, but most of the comments and conclusions are equally relevant to other problem areas such as transportation planning and structural design.

The entire engineering design process must be examined to learn how computers and computer methods can most effectively contribute to an engineering economic analysis. We take the broad view that the study of engineering economy must be concerned with the totality of the engineering design process; otherwise, we would be guilty of not adopting the proper systems approach with which this paper is concerned.

The problem of locating and designing a roadway facility is composed of a large number of smaller but complex and interrelated problems. This is indeed what makes the total or combined problem both interesting and challenging. For example, the total highway design process involves different levels of analysis such as network planning, link location, and final geometric design. Decisions at one stage must anticipate, and be made in awareness of, decisions at other stages. The highway design process can be characterized as being an information system in which large amounts of information are collected, stored, retrieved, processed, and displayed. Decisions are typically made under uncertainty. Determining the location of a proposed road requires more than just the consideration of construction, maintenance, and user economic consequences. Social, aesthetic, and political consequences must also be determined and accounted for in the decision-making process.

ROLE OF COMPUTER AND RELATED TOOLS IN DESIGN

Many basic changes have occurred in the use of computers since their introduction to engineering design in the mid-1950's. Initially, computers were used solely to relieve the engineer of tedious computational burdens. Earthwork end areas were calculated and averaged to obtain volumes of cut and fill. This initial idea of only using a computer as an exceptionally fast calculator fortunately changed with the tremendous increases in computational power introduced in the 1960's. R. W. Hamming (3) states:

> Another argument that continually arises is that machines can do nothing that we cannot do ourselves, though it is admitted that they can do many things faster and more accurately. The statement is true, but also false. It is like the statement that, regarded solely as a form of transportation, modern automobiles and aeroplanes are no different than walking. One can walk from coast to coast of the U.S. so that statement is true, but is it not also quite false: Many of us fly across the U.S. one or more times each year, once in a while we may drive, but how few of us ever seriously consider walking more than 3000 miles? The reason the statement is false is that it ignores the order of magnitude changes between the three modes of transportation: we can walk at speeds of around 4 miles per hour, automobiles travel typically around 40 miles per hour, while modern jet planes travel at around 400 miles per hour. Thus a jet plane is around two orders of magnitude faster than unaided human transportation while modern computers are around six orders of magnitude faster than hand computation. It is common knowledge that a change by a single order of magnitude may produce fundamentally new effects in most fields of technology;

thus the change by six orders of magnitude in computing have produced many fundamentally new effects that are being simply ignored when the statement is made that computers can only do what we could do for ourselves if we wished to take the time.

The design of a system, be it a transport system or an engineering computer system, involves 2 fundamental and highly interrelated steps: first, the design of the components of the system and, second, the design of the interaction among these components. Generally, these interractions are highly complex and difficult to quantify. The problem that was attacked in the precomputer age and also in the formative years of computer use was the component design problem. Component interaction was largely ignored. This forced the designer toward suboptimization. Although optimal components were realizable, total systems were not being designed. The computer is beginning to allow the designer to approach the total problem.

Three terms, almost always mentioned in connection with computers and engineering design, are computer-aided design, optimal design, and automatic design. When he is first introduced to computer methods, an engineer often has the notion that computers provide easy and direct optimal design, and if not optimal, then, at least automatic. This type of individual, generally, looks on the computer system as a replacement, not as a potential partner. The tremendous investment now being made in the development of integrated engineering design systems such as Integrated Civil Engineering System (ICES), however, is concerned not with automatically producing optimal or even feasible designs but with augmenting an engineer's creativity so as to enable him to produce better and more imaginative designs more efficiently. Most design problems associated with transportation, structural, and water resource systems are so complex and involve so many variables that improved design can best be achieved by permitting an engineer to investigate in some detail a large number of design alternatives. It is also clear that only when a large number of feasible alternative design configurations exist can engineering decision-making techniques be meaningfully and effectively utilized. The objective of computers and their related tools is to produce effective computer-aided design that will expand not only a designer's productivity but also his creativity.

Computers and computer models can be used for prediction, evaluation, search, or planning. Each use is different, and each requires a slightly different strategy. Perhaps most important, each use successively requires a more elaborate setting, a more extensive set of assumptions, and more detailed design.

Computer models are used most commonly for prediction. In this case, only performance measures are used, and output is mostly in physical terms such as trip distributions or geometry calculations. A great deal of engineering intervention can, and usually does, take place. The engineer can use his intuition and judgment to check the values that are obtained from the model. An experienced designer can sometimes intuitively evaluate the design and make appropriate corrections or additions to improve it.

A computer model that incorporates evaluation must by nature be more complex and more sophisticated. Unlike prediction that requires no point of view or definition of objectives, evaluation requires the identification of objectives by which goal achievement is determined. Values for various performance variables must also be defined. Evaluation is a great deal more exacting than merely predicting physical consequences.

Search or optimization involves still another level of complexity. To relate the model with the real world requires that controllable variables be identified and information obtained on how and over what range are they controllable, and to what extent will they actually produce real-world effects. To date, there have been few attempts on the part of highway engineers to "optimize" within the highway location process. Various applicable optimization techniques do exist, however, such as dynamic and mathematical programming. Both of these techniques depend on well-formulated and well-behaved computer models of the location process that, to date, are still largely unavailable.

A designer should approach the computer as though each use deals with a completely original problem, involving creative thinking and the application of judgment, imagination, intuition, and experience. The computer system should be designed not to produce solutions but to supply meaningful measures of the consequences of a decision. These responses provide the engineer with a basis for evaluating whether or not his decision has been a good one.

A number of characteristics of advanced engineering computer systems now being developed satisfy, at least in an initial significant step, the previously implied design requirements. Three of these capabilities described are problem-oriented languages, remote computing and time sharing, and graphics. A number of important capabilities associated with areas such as information storage and retrieval, data structure and transfer, and program and system modularity are equally as important and interesting, but these are not discussed.

ENGINEERING LANGUAGES

The designer must control the computer system and specify what information-processing operations should be executed and what results should be supplied. To perform this, he needs a flexible, efficient communication language to enable him to converse with the computer. This language should be oriented toward the designer and the problem he is solving rather than toward the computer or the programmer. Communication languages designed for the user of a computer system are commonly referred to as problem-oriented languages.

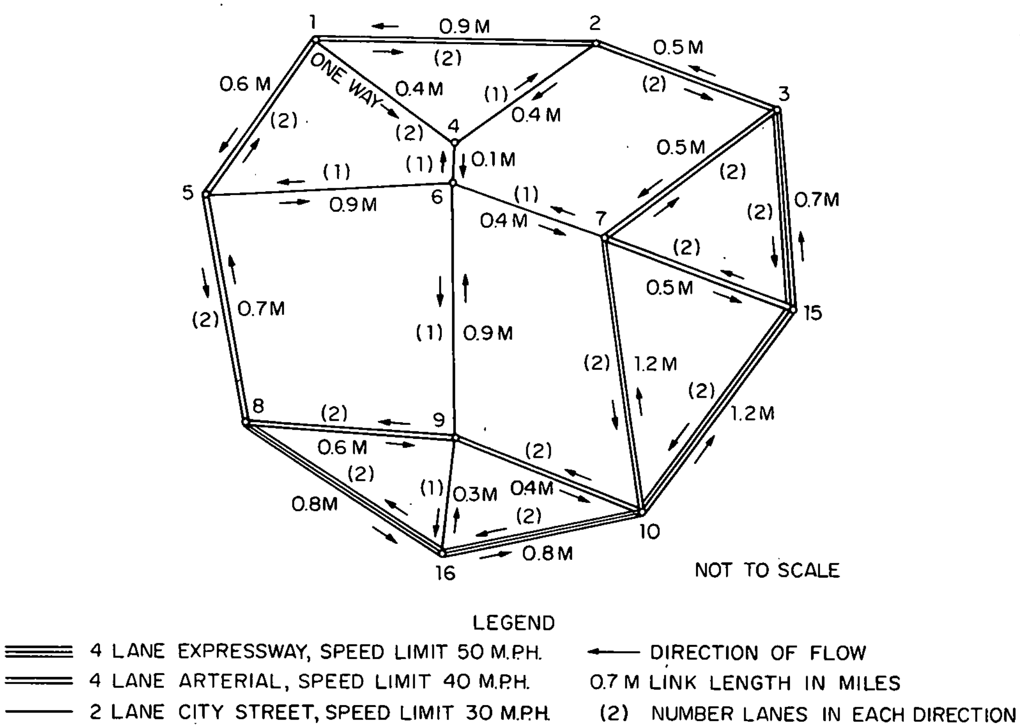
A problem-oriented language contains commands, each one a request to perform some design operation. The command vocabulary of an engineering problem-oriented language consists of technical terms that have meaning to the designer. By specifying a certain sequence of commands, the designer instructs the computer as to which operations should be performed and what information is desired. Problem-oriented languages are easy to learn and use, requiring no conventional programming experience. This idea is important because it can introduce computer systems to designers who might not normally take advantage of such capabilities.

Figure 1 shows an example from ICES TRANSET, a language for transportation network analyses. In TRANSET, it is possible to easily modify a network or to study a number of different networks to determine the effects of network changes on travel times and transportation costs. Because the basic interzonal travel demands may be uncertain, the effects of different demand matrices can be investigated to determine the sensitivity of a design decision to this uncertainty.

TRANSET is one example of a problem-oriented language. Many other languages have been developed for civil engineering as well as for other areas: ICES and STRUDL for structural design and analysis, ROADS for highway location and design, COGO for coordinate geometry problems, and TRAVOL for traffic volume data analysis.

An engineering, command-structured language provides more to the designer than ease of problem specification; it allows him considerable freedom in how he can use the computer and permits him to adapt the computer system to the requirements of his problem. A designer chooses which commands to use, the order of their use, and the associated data. Two designers might solve the same problem using totally different sequences of commands. With a problem-oriented language, the quality and efficiency of the computer usage is dependent on the ability of the user and the commands he chooses. An engineer can specify the known information, the operations to be performed on that information, and the desired results. Problem-oriented languages provide the designer with an effective way of communicating his operational requests to the computer.

The command structure of a problem-oriented language reflects the incremental nature of the design process. Designers build up a solution by performing incremental operations over a period of time. Each new operation is based on the results of the previous operation. The fundamental concept of a problem-oriented language is that all commands or operations are always available to a designer so that he can incrementally build up a solution by making operational requests in many different, unpredictable ways.

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TRANSET
$       FORM A NEW NETWORK BY ADDING LINKS TO THE UNLOADED NETWORK
MODIFY NETWORK 'UNLOADED', FORMING 'PROPOSED' ADD LINKS 2 6 0.6 2 2, 6 2 0.6 2 2
EDIT NETWORK
$       SET UP AND EXECUTE A TRAFFIC ASSIGNMENT
STORE NETWORK 'PROPOSED'
LOAD TRIP MATRIX 'TEST'
SAVE ASSIGNMENT RESULTS IN NETWORK 'DESIRE'
INTERMEDIATE PRINTOUT EVERY 100 ITERATIONS
SAVE RESTART DATA ON DISK
USE INCREMENT 10 TRIPS
REQUEST INTERMEDIATE LINK USAGE FOR LINKS 8 9, 2 4, 2 6
ASSIGN BY PATH MODE
REQUEST FINAL PRINTOUT OF LINK VOLUMES   FROM NETWORK 'DESIRE' FOR ALL LINKS
REQUEST FINAL PRINTOUT OF SYSTEM TRAVEL FROM NETWORK 'DESIRE'
$       SET UP AND EXECUTE SELECTED MINIMUM PATHS
OUTPUT PRINTOUT OF MINIMUM SEPARATIONS AND TRACES
SELECT MINIMUM TIME TREES, ORIGIN ZONES 3, 8
ERASE NETWORK 'DESIRE'
FINISH
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Figure 1. Example of a problem-oriented computer language.

REMOTE ACCESS, TIME-SHARING

A designer must have the ability to interact freely with the computer system. He must be able to build up the design process in an incremental manner, solving portions of the problem, checking interactions of his system components, recycling, and so forth. This requires constant access to the computer during design.

Time-sharing is basically the use of a single computer by several people at essentially the same time. A number of engineers in different, remote locations may use the same computer in such a way that it appears to each that only he is utilizing the machine. The user converses with the computer by means of a console and receives output from the computer at the console. These remote consoles, which are basically some form of typewriter like a teletype machine, are linked to the computer via telephone lines. The individual users share the computer, not in the sense that each has access to a part of the machine but in the sense that each is given the whole machine for brief periods of time on a rotating basis.

Although typewriter console time-sharing is certainly convenient and efficient, many applications arise where more sophisticated input and output devices, perhaps of a graphical nature, may be useful. The extension of time-sharing to a highly sophisticated design input-output remote interactive station at which the designer can perform many different types of data manipulation and presentation is considered to be an important next step.

The most obvious advantage gained from time-sharing is the quick turn-around time provided, i.e., no long waiting periods between the submitting of input and the obtaining of results. The most important benefit of time-sharing, however, is not that it provides a convenience to the user but that it permits continuous man-machine interaction during the design process. This cannot be accomplished through a batch-processing mode of operation.

An essential fact implied by the term design is that the designer does not at first fully understand his problem. He solves it by an iterative process that involves the making of tentative decisions, the evaluation of the consequences by analysis, and then the changing of the original assumption or decisions. As the solution progresses, he defines the problem more precisely by adding to or modifying the original data. He must have a variety of analytical techniques available, so that the refinement of analysis can be increased as the problem description becomes more complete and the solution is approached. The use of a computer in this kind of flexible problem-solving environment becomes much more feasible through time-sharing. In a batch-processing mode of operation, the time delays between modifications in problem data or alternative analyses is a very restrictive factor, and the engineer is compelled to accomplish as much as possible in each computer run. Thus, partial solutions or the investigation of alternative designs are discouraged, and the engineer is often forced to accept something less than the best.

Although there are considerable benefits to be gained from time-sharing and problem-oriented languages when these capabilities are used separately, their real benefits are realized when they are combined. The flexible, efficient communication capability possible with problem-oriented languages coupled with the accessibility and interaction possible with time-sharing enables a designer to utilize computers more effectively in the design process.

GRAPHICAL DISPLAY AND PLOTTING

The results of most design studies are presented in the form of drawings for several reasons. First, graphics permit relationships to be visually appreciated. The overall picture is more readily apparent in a plot than in the obscurity of large masses of numerical information. Second, drawings tend to point out errors that otherwise might not be detected. Last, a graphical representation helps to convey to an engineer those design details that permit him to decide on modifications to improve an existing design.

Plotters and other input-output devices for engineering design and decision-making in conjunction with electronic computers have had an enormous increase in use during the past few years. A discussion of several aspects relating to the use of plotting devices may be helpful.

First, there are as many kinds of plots as there are draftsmen drawing them. Highway engineering plots include geometry or plan views, profiles, cross sections, and perspectives. Data presentation plots may include production functions in a 2- or 3-dimensional view and other linear information such as mass-haul ordinates, cumulative earthwork quantities, and local cost figures.

Second, computer-produced plots can be used for several purposes including final plans and engineering decision-making. Many of the cross-sectional plots are produced primarily for the set of construction drawings. Here, eye appeal, line quality, sheet layout, and aesthetics have been considered to be extremely important. Decision-making or sketch plots, on the other hand, are intended primarily to aid the designer and do not require a great deal of eye appeal and high-quality lines. The principal value of computer-produced plots comes from their use in decision-making.

Finally, an extremely wide variety of commercial plotting devices are available. These include line printers to produce fast, low-cost character plots; table and drum digital plotters to produce ink line drawings; and various types of low- and high-cost display scopes. Each type of plotter has a certain set of performance and cost advantages for a particular plotting application.

One of the most exciting, and probably the most important, developments in graphics is the use of a cathode ray tube (CRT) display scope in conjunction with a light-sensitive instrument called a light pen. A designer working at a CRT scope can directly input data to the computer by drawing on the face of the scope and can also have computed results presented to him in graphical form. Highway design is largely a graphical process and, as demonstrated, requires much iteration and interaction. It, therefore, serves as an excellent example as to how a CRT scope with light pen input might be utilized for engineering decision-making.

The display console is excellent for comparing designs. Alternate horizontal alignments may be shown on the same contour map; graphical results such as mass-haul diagrams may be shown side by side. The engineer can use the light pen to indicate the combinations of parts of several designs into a new design alternative. The cycling, changing, combining, and comparing process can be continued until the engineer is satisfied with his design. The design of the roadway templates could proceed in much the same manner. The computer automatically chooses templates when certain standard conditions are met, and the engineer designs or modifies for exceptional cases. Once the template design is complete, construction cost estimates and user costs can be calculated in detail. The engineer can take a simulated trip on the highway by having driver's eye views in perspective displayed on the console screen. Through such views, safety factors such as sight distance can be reviewed. The computer-aided process is much the same as the traditional design process except that the engineer can produce more alternative designs quickly and evaluate them in greater detail.

ADDITIONAL AIDS TO ENGINEERING ANALYSIS AND DESIGN

The major improvements in the use of computers for engineering design and analysis are likely to result from improved communication and accessibility. Significant improvements are also likely to be made in the range and capabilities of the engineering systems that are available.

Computer users in the past have been concerned primarily with a computational program or a routine. In the future, this concern is likely to be with an information-based system in which all project-related data are stored, and many individual routines are integrated. In solving any particular problem, an engineer may use only a small part of a system or he may use many different systems, automatically transferring data among different systems. ICES constitutes a significant step in this direction. A possible future ICES subsystem might be concerned with costing, economic analysis, and decision-making.

Existing programs and systems have been primarily concerned with the prediction of physical consequences in such terms as cubic yards of earth, pounds of structural steel, or minutes of travel time resulting from an alternative design. In the future, the range of applications will likely be broadened to include other steps in the design process such as evaluation, decision, and search.

Few, if any, highway location and design computer systems now include costing routines. Consequently, if costs are not immediately available, economic analysis routines are difficult to utilize. As management-oriented information systems are gradually introduced, improved cost data will become available and thus facilitate economic analysis and other quantitative decision-making methods.

A technique that appears to be very useful in the decision-making process is statistical decision theory. Statistical decision theory makes use of the Bayesian concepts of probability theory for the handling of uncertainty in connection with the prediction of future events. Decision theory is particularly useful in the context of hierarchical analysis. For instance, the design of a transport system is related to the design of a highway network, which is contained within the transport system, and the design of a highway network is dependent on the design of each of the roads in that network. Because the design of the higher level projects is fully dependent on the design of the lower level projects, decision-making at the higher levels cannot be undertaken without a degree of uncertainty as to the value of certain variables from the lower processes that have not yet been designed. Decision theory proceeds from higher to lower levels in a multistage process. At each state, the decisions are based on certain a priori values of the variables. The decisions made in the higher level processes are used to undertake lower level analyses. Through the use of more accurate predictive models, these prior estimates of the values of the variables are now subject to revision and improvement. Therefore, a review on the basis of these improved values is in order for the higher level decisions.

Simulation, both probabilistic and deterministic, is an example of a mathematical technique that is not possible manually but that has become increasingly useful with computers. Traffic simulation on a roadway attempts to model probabilistically the interactions and complexities of the theory of traffic flow. Traffic simulation can be used to investigate a large number of factors such as average speed, maximum capacity, average delay, deviations and distribution of delay among vehicles, number and types of vehicle interactions, queue lengths, and rates of formation and dissipation of queues. Values for parameters are obtained by randomly sampling from distributions and assigning these values to individual drivers. The drivers then perform according to rules determined by the values. The M.I.T. Vehicle Simulation System, originally developed by Lang and Robbins and now incorporated in ICES ROADS, is a deterministic simulation of a vehicle operation such as resistance versus speed, power, and fuel versus speed. The simulation is performed by incrementing either time, velocity, or distance and computing the resulting changes in the vehicle's operations. A third type of simulation model combining both deterministic and probabilistic elements is traffic assignment. Simulation often allows the building, for the same effort, of a much more complete model than one that can be obtained either through data collection or, in the case of probabilistic models, analytically.

An additional area in which computer usage is likely to increase is that of alternative searching and optimization. The search process in engineering is a very subjective one and is, therefore, difficult to model for a computer. On the other hand, countless alternatives exist in highway engineering and it is difficult if not impossible to distinguish among them. Searching for reasonable alternatives is within the realm of feasibility for computers. In fact, one can make a good case for the position that computers are more efficient at this process than man himself. Man is typically biased, and it is difficult in general for him to reassess a problem from a new standpoint. Good alternatives are frequently overlooked because they are hidden within a forest of permutations. The highway location problem is no exception. There are literally an infinite number of possible horizontal locations for a highway all within a given set of design standards. For each of these horizontal alignments, there is a large number of possible vertical alignments. It is difficult, if not impossible, for an engineer to distinguish all of these alternatives in his mind and to search out the one that is best.

Properly designed search algorithms can be formulated and can be successfully used in the search process. These range from heuristic search processes—a strategy, a simplification, or a rule that attempts to produce a solution that is good enough most of the time but not necessarily optimal—to more or less standard optimization techniques such as linear, integer, and dynamic programming.

SUMMARY

This paper has examined the role of computers and related tools in engineering decision-making and economic analysis. Emphasis has been placed on current computer systems advances and on new techniques of analysis now being implemented or under development. These techniques include problem-oriented languages, time-sharing, graphics, costing, decision-making, simulation, and search. The intent has been to present, and at the same time to give some background for, the current state and the likely trend of future developments in each of these areas.

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Discussion

James Spencer

Would it be possible to give a thumbnail sketch as to how ICES approximates vehicle operating costs on a particular link or on a particular minimum time path between a pair of zones?

John Suhrbier

The vehicle performance capabilities in ICES ROADS consist basically of 2 models, a vehicle model and a driver-traffic model, that have been coordinated to produce results better and more comprehensive than those either could produce alone. No entirely new methods have been developed for ROADS; rather, a number of existing methods have been improved, made compatible, and linked together.

The vehicle model is based on a deterministic simulation of individual vehicles being driven along a roadway. Data used in the simulation include the horizontal, vertical, and cross-sectional geometry stored in the ROADS data tables; as much traffic volume information as is available; and additional roadway description items such as pavement type, passing limitations, and side restrictions. The model represents highway vehicles having internal combustion, gasoline piston engines. Vehicle performance is simulated at increments of time, Δt, and is based on balancing the forces acting on the vehicle.

The driver-traffic model is tabular in structure and is designed to predict the general effects of driver performance on factors such as average vehicle speed. This is accomplished through the use of generalized travel-time, traffic-volume curves.

Paul Roberts

About 3 years ago the Brookings Institution sponsored work at Harvard on the role of transportation in economic development, which led to the development of two specific models. One model, the macroeconomic model, behaves in the same way as the real economy of a country. The second, the transport model, responds like the transportation system. These two models are operated together. First, the macroeconomic model simulates the way the economy operates for a year; it then gives its regional industrial supply and demand information to the transport model. The transport model simulates transportation operations for a year, computing transportation costs to each of the industries. These industry costs are then given back to the macroeconomic model, which uses them in computing industry costs, profits, and a variety of other system-wide economic indicators. The macroeconomic model then repeats the cycle for the second year, and so on through time. In this way, the economy is simulated through time.

The most important aspect of the model is its response to externally applied stimuli. It will react if you do certain things to it. It is clear that one road does not make or break the country's economic development program, but it may be part of a system that does. We recently completed a study for the Colombian Government in which we developed a program of investment priorities for the next 10 years. The government's basic problem was to decide where it should spend its money, how much it should spend, and what would happen if it spent money in certain ways. We went to Colombia and gathered the necessary data; then, we calibrated the model so that it would replicate the actions of the economy over the years 1956 to 1965. Next, we fed into the model a series of alternative time-staged development plans. Finally, we compared these plans one with another to see which we liked the best.

Even though there are many operational problems in models like these, we have learned a great deal about that economy and what can be done to make it work as we want it to. We think these studies are useful. We also think simulation as a technique can be used to help solve a variety of problems at the national level, the city level, the regional level, or even at the level of a single highway, an isolated intersection, or a single parking lot. Of course, working at the national level, you could be preparing to invest $2 billion or so over 10 or more years, in which case computer studies make good sense. However, at the parking-lot level, you could spend $150,000 for computers, while the investment to be made is only $50,000. The example is contrived, but it indicates the range of models we could be using in economy analyses. Naturally, there is a level of detail beyond which you cannot go with this kind of model. You cannot say whether it is better to use chipstone or river-run gravel. The model can be used, however, to answer the larger questions about what is likely to happen as the system is changed.