Application of Operations Research to Highway Problems

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The basic character of operations research is described briefly as an attempt to conceive of specific problems as problems in the area of decision theory. In terms of this characterization, a question is raised regarding the role of operations research in the analysis of highway problems.

The operations research approach is compared with the "traditional" approach to highway problems. Finally, mention is made of some of the difficulties associated with taking the former approach in the area of highway research.

• THE CIVIL ENGINEER, since he first divorced himself from military engineering in the 18th Century, has been concerned with public works such as the design, construction and maintenance of highways. As other specialties in engineering have developed, the civil engineer has maintained his early interest, and now finds himself in a position of increasing national importance as the demand for and cost of highway facilities increase. As in other branches of engineering, the civil engineer finds that his decisions have far reaching consequences for the entire community. Many social and economic problems must be solved in conjunction with technical engineering problems to develop a community highway transportation system.

Managers in many fields, faced with increasingly complex problems, have utilized a new branch of science as an aid in arriving at problem solutions. This field is known as operations research. In spite of all that has been said and written about operations research (*3, 7, 8*), confusion persists, both among those who do it and those who sponsor it, as to the research process and the expected outcomes. Sponsors may be confused because they think they are engaging engineers who can apply existing theory to their problems, and are disturbed by the slow and difficult course of theory development by research. Researchers may be confused by conflicting philosophies of theory construction (*2, 9*) and the application of the techniques they have learned in their own fields to new and complex problems.

In spite of these difficulties, however, operations research has provided a means of using the methods of science to solve problems in areas in which they had previously been dealt with by less powerful and less objective means. In civil engineering, for example, the use of scientific principles, developed in physics, has long been accepted practice in the design of structures. The possibility of using scientific principles to determine whether or not a structure should be built at all, and the probable consequences for a community of building a structure of specified characteristics in a given location has not been as generally recognized.

Operations research provides a procedure for dealing with the broad social and economic framework of technical problems. It began as an organized activity just prior to the start of World War II (*8*), although its central concepts may be traced back to the work of F. W. Taylor in the development of "scientific management."

The first operations researchers were scientists who helped integrate radar, then being used for the first time, into the

aircraft early warning system in Britain. Physicists, electrical engineers and others who had designed the equipment were assigned to the radar sites to maintain and operate it, and train military personnel in its use.

Once the equipment was in operation, the scientists became interested in its tactical use, and worked informally with the operating people to develop procedures for integrating the radar into the early warning system. Research methods from their own fields were used to solve operational problems. This work was singularly successful, and operational research, as it is called in Britain, was formally established. For the rest of the war, representatives of the physical, social, behavioral, and biological sciences assisted military planners in making operating decisions about the utilization of national resources, such as troops, ships, and aircraft.

Since that time, operations research has been widely used in solving military, industrial, and community problems. Typical examples include retail store operations, complex equipment reliability, negro manpower utilization in the Army, motor freight operations, and port facility utilization (*7, 8*). At The Ohio State University, a study of the community-hospital system is in progress, and Ackoff (*1*) has proposed a study of national planning for India.

The primary objective of an operations research study is to provide systems management with an understanding of the system to aid in exercising system control. System understanding for control implies that system variables have been identified and measured, and that the relationship between them can be expressed in a "model" (*3, 9*). The model is an abstraction of those aspects of the system which are believed to contribute most to the variability of system performance. Ideally the model is a mathematical statement of the relationships between the decision (independent) variables of the system over which the "decision-maker" has some degree of control, and the criterion (dependent) variables, or measures of system effectiveness.

The great utility of the model, as with any expression of the relationships between independent and dependent variables, is its ability to predict the effect of changes of the independent (decision) variables on the effectiveness of system performance. For example, in the highway field, system performance might be measured in terms of congestion, accidents, etc. Independent (decision) variables would include the physical characteristics of the highway, such as number and width of lanes, grade, and sight distance. The model might state the relationship between physical system characteristics and system performance.

The concept of the model is not new to engineers. The equations used in the design of structures are models. What is new is the use of models to solve broad operational problems.

Because operations research investigations routinely include a wide range of variables, researchers from many fields may be found working together as a team. Each brings to bear substantive knowledge and research methodology from his own field, minimizing the possibility that important system variables will be overlooked. Operations research groups may include workers with such diverse backgrounds as engineering, mathematics, physics, sociology, psychology, economics, medicine, anthropology, and philosophy. As an integrated team they apply their research skills to the solution of broad problems.

So much for general background. Consider now some examples of the application of operations research methods to highway problems. One of the most outstanding examples is a study by Edie (*4*), of the Port of New York Authority, on the collection of vehicular tolls. Annual operations savings in excess of ten times the cost of the research resulted from this study.

The objective of the investigation was to determine an optimum schedule for manning toll booths so that a minimum number of toll collectors could be used to

provide satisfactory service to customers, measured in terms of traffic delays at the toll booths. Data on traffic arrivals, service times, and the number of vehicles waiting for service were collected and analyzed. The data were found to approximate a Poisson distribution, allowing for prediction of effects of various changes in policy relative to booth staffing. The schedules suggested by the models were tried in practice and found to meet customer service requirements and to reduce the cost of toll collection.

In another study, the factors influencing vehicular tunnel capacity were investigated (*10*). Capacity was defined as the maximum number of vehicles passing a point under certain restrictions of safety, delay, etc.

As in the previous study, the first step was one of empirically determining actual traffic flow patterns. The objective of the study was to determine the optimum vehicle speed and spacing for maximum tunnel capacity. This was done by first developing a formal model, or series of equations, stating the relationships between traffic speed and density for various types of traffic.

Linear relationships were found to exist between vehicle speed and density, expressed in vehicles per mile. Differences in slope of the speed-density curves were attributed to differences in traffic composition. An analysis of the data suggested policy recommendations to improve the utilization of the tunnel facility. For example, a minimum speed of 20 mph was specified and vehicles unable to maintain this speed were excluded from the tunnel. Because vehicle spacing was critical, markers were placed at 75-ft intervals in the tunnel, and motorists were advised to keep 75 ft apart.

In addition to the work on traffic problems in this country, problems of highway construction, use, maintenance, and safety have been considered in Great Britain. In attempting to determine the highway requirements for future traffic demands, the cost of highway accidents and delays, future traffic pattern, etc., have been considered (*5*).

The studies previously referred to were essentially component studies, in that a limited, specific component of the over-all highway system was singled out for investigation. The system was defined in terms of specific facilities, the New York Port Authority tunnels, in the studies by Edie (*4*) and Olcott (*10*). Policies for improving the utilization of these facilities were established by developing an empirical picture of facility utilization, and fitting these data to formal mathematical models.

In a study conducted by the Operations Research Group of The Ohio State University (*11*), a formal model of the over-all highway system was developed. Initially posed as a question of assessing the costs of traffic congestion, it quickly became evident that the elements of "cost" of congestion were borne by wide segments of the community, and that methods of describing these costs in a community-system context were necessary to provide realistic data to highway decision-makers in allocating community resources to highway facilities. As in most system problems, allocation depends on "trade-offs," or compromises between the amount of resource provided for different objectives.

The relationships between system variables must be known before the "trade-offs" necessary to optimize an over-all system criterion can be made. In order to make these "trade-offs," the variables must be described in the same units of measure. "Cost" was selected in this instance, although the determination of the costs of many of the factors involved is most difficult, and beyond the scope of the initial study. The cost of human life, as it related to the provision of highway safety features, is a case in point. It can be inferred, perhaps, for a given social system by measuring the amount of resources expended to preserve it by providing safety devices.

Two "decision models" were developed for use by highway designers. The first model assumed that the total cost of the highway was the sum of the costs of construction and maintenance of high-

ways, and of delays to users of the highway and to non-using consumers of the facility, such as local industries and residential areas. These costs were assumed to be functions of highway capacity.

The second model was concerned with the relationship between an "aggregate social cost" and highway design variables. This cost included the following general cost categories: operating expenses for vehicles, cost of transit time for vehicle passengers and drivers, cost of accidents, capital recovery on investment in highway construction, and cost of highway maintenance, operations and administration.

A procedure for evaluating the approximate monetary value of transit time for passenger automobiles was developed. This evaluation was based on the notion that a highway may be classified as "satisfactory" in terms of an aggregate social cost to the community and users of the facility. Given a "satisfactory" highway, the value the community placed on safety, delay, etc., could be deduced from the amount of its resources it was willing to spend to assure that these criteria are met.

Two different phases of operations research can be identified in the foregoing studies. In the first two (*4*, *10*) value judgments were made as to the criterion of good highway system operation (that is, the greatest utilization of the highway facility as measured by numbers of vehicles moving through the facility in given time intervals). This was assumed to be a valid measure of the utility of the tunnel. Empirical data collected showed that the actual usage patterns closely approximated statistical distributions with known properties. Inferences were drawn about the effect of variations in physical highway system variables on the service provided by manipulation of the models or statistical distributions which had been found to closely approximate actual conditions. Predictions were made about the effect of changes in highway utilization policy, and put to empirical test. It was found that actual results closely approximated predicted results, thus validating the models.

In the third study (*11*), a general criterion measure of social cost was assumed and the elemental cost increments comprising this social cost were specified. Using this criterion, or dependent variable, a mathematical model comprising linear differential equations was proposed as a means of determining the values of the design variables of the highway system for minimum social cost. This mathematical minimum would approximate the actual social cost minimum only if the model were a valid one. The assumptions of the model must be validated empirically before it will be a useful device for the highway designer. The formalization of the problem was necessary, however, as a first step to determine what empirical data to collect. Pinpointing the need for specific data is important in minimizing the cost of research.

SUMMARY

In summary, the over-all objective of the highway system may be viewed as one of providing safe, rapid transportation at minimum direct and indirect cost to both private and public users. A number of criteria for such a facility may be chosen, such as a "satisfactory standard of service" or "social cost." Either of these criteria imply the availability of quantitative information on variables, direct measurement of which may be difficult or impossible. The task of operations research is one of developing criteria for those aspects of the system which can be measured, and providing the decision-maker with measures of subsystem criteria (*6*). The function of the system manager is one of deciding on the best combination of system resources to achieve the over-all objective.

In the work done at The Ohio State University, the first step in the formulation of the over-all highway problem has been completed (*11*). It now remains to determine empirically the actual relationships between the elements of social cost and the parameters of the highway. This will be a difficult task because of

the measurement problems imposed by such concepts as safety and delay. It will also be complicated by the fact that no road is independent of the other roads in a network, and the interactions between highway facilities must be determined.

In spite of these difficulties, operations research techniques point the way to highway system solutions which will allow a community to make decisions about the allocation of its resources to the highway system based on the expected effectiveness of the system to provide safe, rapid transportation at minimum cost.

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REFERENCES

1. Ackoff, R. L., "Operations Research and National Planning." Operations Research, p. 457-467 (1957).
2. Bronowski, J., "The Common Sense of Science." William Heinemann, Ltd., London (1951).
3. Churchman, C. W., Ackoff, R. L., and Arnoff, E. L., "Introduction to Operations Research." John Wiley and Sons, New York (1957).
4. Edie, L. C., "Traffic Delays at Toll Booths." *Jour. Operations Research Soc. of America,* 2:107-138 (1954).
5. Glanville, W. H., "Road Safety and Traffic Research in Great Britain." *Jour. Operations Research Soc. of America,* 3:283-299 (1955).
6. Hitch, C., "Suboptimization in Operations Problems." *Jour. Operations Research Soc. of America,* 1:87-99 (1953).
7. McCloskey, J. F., and Coppinger, J. M., "Operations Research for Management." Vol. II. The Johns Hopkins Press, Baltimore (1956).
8. McCloskey, J. F., and Trefethen, F. A., "Operations Research for Management." Vol. I. The Johns Hopkins Press, Baltimore (1954).
9. Minas, J. S., "Formalism, Realism and Management Science." *Manag. Sci.,* 8:9-14 (1956).
10. Olcott, E. S., "The Influence of Vehicular Speed and Spacing on Tunnel Capacity." *Jour. Operations Research Soc. of America,* 3:147-167 (1955).
11. Vaswani, *et al.,* "An Investigation of Highway Economics." Engineering Experiment Station, The Ohio State University (in press).

DISCUSSION

Ram Vaswani, *Assistant Professor, Dept. of Industrial Engineering, North Carolina State College, Raleigh, N. C.* — Professor Howland has cited highway research done by Edie, Glanville, Olcott, and Vaswani, and has suggested that "workers with such diverse backgrounds as engineering, mathematics, physics, sociology, psychology, economics, medicine, anthropology, and philosophy" work together as teams on highway problems. One of the most disconcerting omissions in his paper, however, is any indication that he recognizes problems and conflicts which arise in teams composed of experts from diversified fields, or even from allied or identical fields. Whatever the true reasons for this omission might be, the sponsors of highway research should be made aware of the weaknesses of multi-

disciplinary operations research teams.

Because the highways are the nation's arteries, they deserve a high priority on the research effort available. For this reason, sponsors of highway research should reexamine their plans for prospective research commitments and not permit themselves to be carried away on high hopes created by fallacious association between team research and sure and successful solutions of all difficult problems.

The pitfalls of team research have received considerable attention in the sociological and psychiatric literature and a reader interested in supporting, or indulging in team research will be well advised to read Blackwell (*1*), Bronfenbrenner and Devereux (*2*), Caudill and Roberts (*3*), Redlich and Brody (*4*), and Wohl (*5*) before making a decision. More recently, the subject of team research has begun to be discussed in operations research literature also (*6*).

In recent years many universities have established research teams. The reasoning behind this approach seems to be that since one person cannot be expected to know all phases of science and technology, putting together of several heads with diversified training and backgrounds will make the group a synthetic, whole research unit. Thus, it has become fashionable for operations research groups to include in their teams historians, psychologists, sociologists, physicists, philosophers, anthropologists, mathematicians, engineers, etc. As a professor at one of the leading mid-western universities recently remarked: "These groups feel that forming a team of 'experts' from diversified fields is the most important step in the solution of a problem; that once this step is taken, research will take care of itself."

The financial burden imposed on the sponsors by such a practice is obvious and does not warrant any discussion. Suffice it to say that the current practice of some operations research groups requiring the employment of multidisciplinary teams puts operations research out of reach of clients with modest means.

In the discussion which follows, the history of development of operations research teams is traced and the reasons for the success of these early teams are discussed. Then, the difference between those early days and the present time is discussed and the reasons which make operations research teams ineffective now are pointed out.

The term "operations research" sprang up during World War II when scientists from diversified fields were called on to aid military commanders in increasing the effectiveness of the armed forces. Several factors contributed to success of these multidisciplinary research teams. First, the scientists were highly motivated to give their best during the national emergency. If there were any interpersonal difficulties, these were subordinated in national interests. Every participant was aware of the fact that because the war was of limited duration the team research activity was temporary. Hence, no long-term interests were involved.

For many scientists, who had spent most of their working lives in laboratories and classrooms, the novelty of attacking real life problems was stimulating. In the typical academic tradition, the scientists were not ashamed of confessing their ignorance of military matters and were anxious to obtain help from appropriate sources to enable a quick solution of problems to be reached.

Because military research was of a highly classified nature, publication of results was out of the question. Hence, one of the major causes of bitterness and demoralization — the question of authorship credit — was absent.

In industrial operations research, however, the story is quite different. Young men and women with previous academic training or field experience in operations research and allied disciplines are entering operations research groups with the idea of making a career in this line. In most cases, there is no reason to expect that personal interests will be subordinated to group interests. These facts alone are sufficient to bring to mind sev-

eral causes for difficulties and cleavages in group research efforts.

Inasmuch as group research is expensive, its launching usually is accompanied by much fanfare. Many disciplines are brought together without any preplanning. At group meetings, communication is reduced to the barest minimum level so everybody can understand everybody else. "Group-think" tactics often necessitate orienting team members with high school or freshman mathematics, without any evidence of success. As a friend once remarked: "The good researchers are held down to the level comprehensible to the dummies in the group."

In spite of these handicaps, if the group is fortunate in having an intelligent and competent supervisor — a detail which the sponsor has no way of knowing — matters can be kept under control, at least for a while. However, when the supervisor is ashamed of confessing his ignorance about matters which for some reason he feels he ought to know, the conduct of group research becomes a completely meaningless activity. In an effort to conceal his ignorance, the supervisor tries to recede from the group. He accomplishes this by delegating authority for research: strict hierarchical echelons are set up, with the result that resentment against the chief increases. The hierarchical camouflage hastens the breakdown of communication and all hopes for taking corrective action cease.

Emotional difficulties mount up when the individual members realize that their creative efforts are being discouraged or belittled by the supervisor. Also the attendance, and presentation of papers, at society meetings and publication of papers by group members is prohibited under the convenient excuse that all work produced by a group member is state property. In all this, the sponsor's problem is somewhat forgotten, overlooked, or distorted.

Finally, the day of judgment arrives. It is time to write a report, embodying the results of research for submission to the sponsor. When the report is to be submitted under joint authorship and the work has been carried out by one or two lone members, only skillful maneuvering on the part of a supervisor can save the day. Being under pressure to justify his own status and the existence of a research group, the supervisor feels compelled to transgress the rights of the individual worker who produced the work, and tries to pass off this work as a package manufactured by the group acting in unison from start to finish. This artifice also serves to justify to the sponsor the salaries drawn by the "by-standers" in the group.

Every effort is made to conceal from the sponsor the blunders and shortcomings of group research. Thus, if a sponsor's project is addressed to one problem and if because of incompetency of the group no work on this topic is produced, this fact is not brought to the sponsor's attention. Instead, this incompetency is camouflaged with wordiness and incomprehensible mathematics and an attempt is made to substitute another problem as an absolute necessity.

Why must organized team research be superior to individual research, as the advocates of team research assert from time to time? Can the mechanistic concept of Taylor (*1*), requiring that manual jobs be broken down into smaller components, to be assigned to individuals, be extended to research activity? Can the assembly line technique of mass production requiring each researcher to deposit his brain effort on the line be effective? Can successful ideas be produced by brainstorming and bull sessions rather than by individual hard thinking? On this point, Benson (*8*) has the following to say:

> The idea seems to be that, instead of tackling problems with intelligence and logic, businessmen should flock to games, fads, and fantasies, hoping that out of some magic blue yonder they can painlessly pluck the solutions to serious problems. Let us consider for a moment the "let's-all-do-it-together" idea that underlies brainstorming. Doesn't it reflect the fact that our modern education system does not place much emphasis on training us to stand on our own feet as individuals? In an era of committees and study groups, collective thinking and teamwork, there is a tendency to

suspect a man of being an egocentric if he sits down by himself, thinks for himself, and then gets up and speaks out. He is considered an "oddball" who does not "fit into the team."

But deciding whether people should work alone or together should be very simple: If the problem requires a broader range of knowledge and experience than one has in one's own head, there is an obvious advantage in working with people who possess this knowledge and experience. But if the problem requires original thinking, then for goodness' sake let us get off alone in a corner, and think.

The advocates of team research often associate team research with a dedicated group of clear minds working as a unit towards a fixed common objective and cite intellectual stimulation and academic atmosphere as the most important advantage of group research in a university. However, the large voluntary quit rates prevailing in university operations research teams do not support this claim. In two schools located in Ohio, which have operations research groups, a researcher seldom stays for longer than a year. There are exceptions, of course, but mainly these are students working for their advanced degrees who do not have the mobility to change jobs. The very fact that the author, as he announced at the presentation of his paper, was forsaken by his coauthors because of disagreement on the contents of the paper, might be an indication of tensions and lack of collaboration. One will ask how a sponsor can be sure of receiving a unanimous research report when three team members cannot collaborate successfully in presenting a joint review paper which does not even contain the original work of any one of them?

To rationalize the high quit rate and deep fissures in research groups, one might start out by examining the motives of persons who join a university research team. Wohl (*5*) has classified the collaborators of teams into the following categories:

1. Persons who feel that the problem falls within two or more disciplines and cannot be dealt with adequately by any one of them.
2. Participants who feel that the problem falls within an unoccupied border zone between disciplines on which particular specialists must concentrate their skill.
3. Participants who were originally drawn into the project because they were obscurely tantalized by its possibilities and because they were sufficiently free of other commitments to have time to participate.
4. Opportunists to whom a chance to collaborate would be an opportunity to help round out an academic empire, to enhance personal prestige, or to establish a reputation for aggressively liberal thinking in their own field.

Wohl also points out that although these last two motives may seem less worthy than the others, they are frequently operative in recruiting an interdisciplinary group.

To Wohl's categories of participants, the writer would add the category of Ph.D. degree candidates who enter a group on high, and sometimes false, hopes of getting an opportunity to work on theses topics. Regardless of their long-term objectives, their immediate objective is to do independent research, write their theses, and publish papers. To achieve their objective, participants in this category put forth their best efforts in the interest of research. Unfortunately, they are also the worst victims of academic exploitation on the part of participants in Wohl's last two categories.

In general, unless the collaboration among experts arises from mutuality of interests and confidence in each other's ability, it is bound to collapse. As Conant (*9*) confessed:

. . . my own attempts to bring about greater integration have for the most part failed. I am now convinced that the only cross-departmental collaborations that are effective are those that arise spontaneously by almost the accidents of the personalities of the various faculties."

The conduct of good and effective team research requires a sincere vigorous man at the helm of affairs, capable of encouraging his staff rather than indulging in academic exploitation for his personal ends. Wohl (*5*) cautions:

This (the direction of team research) requires

both knowledge and tact, and rarer still the patience and skill to work with men maturing their own ideas slowly. I believe that unfortunately there are not many such individuals available and that the shortage limits the amount of successful interdisciplinary research that can be done.

The appointment of older men to jobs requiring such direction, as seems to be the current practice of deans of schools, is not the answer to the problem. The present phenomena are new in character; the world is changing fast and new problems cannot be solved on the basis of the conventional T-maze experiments in the laboratory. Such problems need for their solution new and powerful techniques of analysis and ideation which people whose training has been restricted to traditional education cannot even comprehend.

The 20th Century is one of vastness in every respect — big universities, big manufacturing plants, big corporations. So it is going to be with research; therefore, team research is here to stay. According to *Better Living* (*10*), 91 percent of the U. S. Government grants for research in 1956 went to five universities. Hence, it is important that we discuss and understand the pitfalls in this kind of activity and not, as pointed out by Wohl (*5*), commit the fallacy of attaching a pious significance to team research.

REFERENCES

1. Blackwell, G. W., "Multidisciplinary Team-Research." *Social Forces,* 33:4, 367-374 (1955).
2. Bronfenbrenner, U., and Devereux, E. C., "Interdisciplinary Planning for Team Research on Constructive Community Behavior." *Human Relations,* 5:187-203 (1952).
3. Caudill, W., and Roberts, B. H., "Pitfalls in the Organization of Interdisciplinary Research." *Human Organization,* 10:12-15 (1951).
4. Redlich, F. C., and Brody, E., "Emotional Problems in Interdisciplinary Research." *Psychiatry,* 18:233-239 (1955).
5. Wohl, R. H., "Some Observations on the Social Organization of Interdisciplinary Social Science Research." *Social Forces,* 33:4, 374-383 (1955).
6. Michael, D. N., "Some Factors Tending to Limit the Utility of the Social Scientist in Military Systems Analysis." *Operations Research,* 5:1, 90-96 (1957).
7. Taylor, F. W., "Scientific Management." Harper & Bros., New York (1947).
8. Benson, B. S., "Let's Toss This Idea Up. . . ." *Fortune,* pp. 145-146 (Oct. 1957).
9. "President's Report, 1951-52," p. 18, Harvard University, Cambridge, Mass. (1952).
10. *Better Living,* 11:6, 22 (Nov.-Dec. 1957).
11. Hitch, C., "Operations Research and National Planning — A Dissent." *Operations Research,* 5:5, 718-723 (Oct. 1957).

Daniel Howland, *Closure.* — The effectiveness of this type of research will be judged by results, not by what is said about the research workers. The substantive results in the literature provide the most valid argument for team research in the solution of complex system problems.