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During the 1960's many large cities experienced a 10 to 15 per cent annual rate of increase in demands for urban public safety services, as represented by police, fire and emergency medical services. Such demand increases, coupled with higher salaries and tighter city budgets, required city administrators to seek management alternatives other than simply adding more personnel. Systematic analysis of alternatives to improve performance and productivity have of course been carried out in the private and defense sectors. However, this has not generally been done in the municipal public service sector. Administrators in many municipal public services had simply grown accustomed to adding personnel as the sole management response to be considered. Examining the budget of these services, however, one typically finds that 90 to 95 per cent of expenditures are consumed directly by salaries, pensions and related fringe benefits. Consequently, police, fire and emergency medical services comprise some of the most labor-intensive, undercapitalized industries in the United States today.

One useful measure of the effort allocated toward seeking innovative solutions to problems is the dollar amount spent on research and development. Comparing relative expenditures in research and development, healthy growing industries in the private sector typically allocate 4 per cent of gross revenues to research and development. The Department of Defense usually obligates 10 per cent of its budget (13 per cent in the late 1960's) to research and development. In contrast, for most urban public safety services, at least through the late 1960's, it is difficult to identify as much as 0.1 per cent of total expenditures being directed toward research and development. This has changed somewhat in recent years—due to Law Enforcement Assistance Administration (LEAA) funding in the case of police, Department of Housing and Urban Development funding in the case of certain emergency services, and funding by the Departments of Transportation (DOT) and Health, Education and Welfare (HEW) in the case of emergency medical services. However, much research remains to be done, particularly in areas where no one agency (Federal or otherwise) has had interest or jurisdiction.

Our NSF-RANN research aims at developing policy-related procedures and guidelines for improving the planning and decision-making in urban public safety systems, particularly police and emergency medical services. By focusing on more than one of the traditional urban emergency services, it falls outside the jurisdiction of any one of the specialized federal agencies (such as LEAA, HEW, etc.).

The research effort is broken down into three components:

1. A comprehensive analysis of *evaluation criteria* of urban public safety services, directed toward the understanding of productivity and effectiveness of urban public safety services.
2. Development of a set of *analytical and simulation models* that should be useful as planning, research, and management tools for urban public safety systems in many cities.
3. An evaluation of the *impact of new criteria, methodologies, technologies, and organizational forms* on traditional crime-hazard rating schemes, insurance rating methods, related regulations and standards, personnel performance criteria, system operating policies, neighborhood service indicators, employees and their organizations.

If these research components are envisioned as horizontal "cuts," *police* and *emergency medical services* are the two primary vertical cuts, representing the two specific kinds of urban public safety systems on which the research is focused.

The research is strongly tied to cooperating agencies, especially in the Boston-Cambridge area, and additionally to other agencies throughout the country. It provides a close interaction of university-based research with the operational realities of police and emergency ambulance agencies. This is designed to provide early feedback from agency administrators regarding the underlying assumptions of the research and the potential utility of the research results. It is also designed to shorten the usual 5-10 year span from the inception of a research program, through the development phase, to the successful implementation of the fruits of the research in operating agencies. Current pressures for productivity improvement in the urban public sector almost demand that this time lag be cut to 2-3 years wherever possible.

Successful transfer of research results requires an understanding of the institutions in which change and innovation are proposed. To facilitate the transfer, our research project is concerned not only with developing the technical details of various management and planning tools, but also with obtaining a knowledge of the process of change within the institutions—particularly in urban police departments and emergency medical services. This work requires the integrated efforts of sociologists, contemporary historians, urban planners, police and medical professionals, operations researchers, management scientists and physicists.

An up-to-date account of these efforts can be obtained from our monthly newsletters, which are available from the Project Secretary, Room 4-209, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139.

Due to space limitations, the present paper will focus on the second research component listed above, involving the development and implementation of analytical and simulation models for planning, research and management. The paper will have three major sections. First, we will examine the quantitative tools that have been developed recently, often under the name "operations research," and place them in a larger context. This context will relate to industrial and military applications of similar tools on the one hand, and to broader organizational and institutional problems of urban public safety services on the other.

Second, we will review the methodologies contributing to the development of quantitative models of urban public safety services and outline the structure of one recently developed tool—a simulation of urban police patrol and dispatching.

Finally, we will discuss current public safety implementations of quantitatively oriented planning and management tools developed at M.I.T. The discussions will usually emphasize police applications, although significant activity is under way in the area of emergency medical services.[1] References are given to allow the interested reader to pursue details of methods or implementations that are not discussed here.

Quantitative Tools in Perspective

To place quantitative tools in the broader context of administrative and organizational problems of urban public safety systems, it is useful to review the history of their use or nonuse in public and other systems. The application of operations research and quantitative modeling to agencies with operational problems is relatively new. Most agree that operations research established its first foothold in a military environment approximately 30 years ago. Shortly after World War II it was found that many operational problems experienced in an industrial context could be addressed through the classic steps of an operations research study; define the problem, specify the objectives, define criteria relating to the objectives, specify alternatives, compare alternatives, present results, implement recommendations.

Indeed, both major applications areas of operations research—industrial and military—have been flourishing during the last 20-25 years. Many special topic areas such as inventory theory and transportation science have spun off as individual applied sciences in their own right. In fact, it is a popular notion that operations research is, by definition, a transient applied science to be utilized in substantive areas that have relatively little history or tradition of using systematic analysis. Then, the notion holds, as the knowledge and experience in a particular substantive area grow, work in that area is no longer operations research but rather management science, traffic analysis, logistics analysis or inventory control.

Implementation of operations research studies in military and industrial settings never has been entirely straightforward. But there are many documented instances of successful implementations ranging from revised military tactics during World War II, to modern inventory control systems, to system control procedures for latest generation time-shared computers.

There also are documented cases of difficult implementations and cases where there has been no implementation at all. It is concededly dangerous to generalize over thousands of operations research studies. But it would be fair to say that the majority of successful implementations occurred in instances for which either the objectives and constraints were very well-defined (e.g., maximize profit, minimize probability of system failure) or the analysts took pains to include in their study broader organizational issues. Examples of such issues are impact on personnel training, recruitment and incentives; customers' perceptions, and longer-term implications of the work in terms of how it might fundamentally change the system under study. Many unsuccessful implementations failed to consider one or more of these issues when success or failure would be determined by their degree of resolution.

A third major set of operations research applications that has emerged during the last 2-5 years is in the area of governmental service

[1] For instance, see J. M. Hoey. *Planning for an Effective Hospital Administered Emergency Ambulance System in the City of Boston*. Report RR-01-73, Innovative Resource Planning in Urban Public Safety Systems, Laboratory of Architecture and Planning, Massachusetts Institute of Technology, Cambridge, Massachusetts, 1973.

systems, including urban public safety systems. In these systems today, applications of operations research and systematic analysis are in many ways at the same point as they were in defense systems 30 years ago and in industrial systems 20-25 years ago.[2] Problems of these systems are becoming known, although their complexity has usually precluded precise formulations. The need for new methodologies has become apparent, although work in this area barely has begun. Limited implementation experience already is available, and much of this experience points to a need to consider more carefully than ever the broader organizational issues discussed above in order to provide any chance of successful implementation.[3]

Implementation Difficulties—One may question why the quantitative techniques often referred to as operations research have not had an earlier impact on governmental service systems. The answer to this is multifaceted and difficult to determine fully at this time. However, there are some obvious considerations:

1. Ill-Defined Objectives and Constraints. Objectives, performance criteria and constraints for these systems are very difficult to isolate and define. For urban public safety systems one may state as an objective the "efficient, effective and equitable distribution of quality emergency service within reasonable budget constraints." It is difficult, however, to transform such sweeping statements into performance criteria that are measured easily and into constraints whose possible violation can be determined readily. Moreover, objectives may vary among administrators, operatives and consumers in an urban public safety service.

Travel time may be offered as one possible performance criterion, but its indiscriminate use could result in the assignment of inappropriate personnel in response to a family dispute or in the assignment of inappropriate medical personnel in response to a cardiac arrest, just to save seconds of travel time. Workload equalization among personnel, if followed precisely, could result in gross inequities in the type, quality or rapidity of service delivered to various population groups. One begins to realize that a popular word in operations research, *optimization*, often bears little relevance to operational realities of governmental service systems, primarily because of the difficulties in defining objectives and constraints.

2. Lack of Productivity Measures. Since system objectives are poorly defined, so are measures of system productivity. Signals that an urban public safety system is not performing well are not nearly as apparent as a loss (rather than a profit) in a particular year for an industry or as a large cost overrun in the construction of a defense system. For instance, if one city incurs twice the per-capita crime rate of another city, this may simply mean that the citizens and police in the former city are more likely to report consistently and record accurately crimes that occur; or if a larger crime rate is a fact, it may be due in part to the number of transients who enter the city at 9 a.m. and leave at 5 p.m.

Many measures other than crime rate reflect upon police operations in a city. This fact makes impossible such statements as "City A's police department is better than City B's." Because of a lack of productivity measures, forces within an urban public safety system that would tend to favor the *status quo* often prevail. The alternative of "no change" assures that visible failure will not occur, because these systems have been working in some form for many years. But it also assures that visible progress may be difficult to achieve.

In the context of our research project, the first of the three research components examines alternative measures of performance and productivity, both system-wide and at the level of the individual officer or ambulance attendant, to provide more meaningful measures of efficiency, effectiveness and equity. The complexity of the issues involved requires that several different approaches be used. The approaches include interviewing agency personnel and consumers (performed by Prof. Gary Marx, an urban sociologist at M.I.T.), reviewing the literature from about 1900, analyzing measures and rules of thumb used currently by consulting firms and professional organizations (such as the International Association of Chiefs of Police) and reviewing how various measures have been misused so as to achieve results not desired (and possibly exactly opposite to those originally planned).

3. Internal Resistance to Innovation. These systems with their civil service orientation have tended to be insular, often fraternal, staffed with career employees whose formal education in many cases ended at the high school level. The high degree of job security frequently gives rise to an average of 20 years or more in one agency until either retirement, or (less likely) resignation or dismissal. Thus, the time constants of these systems are very long, often requiring 10 years to achieve a 50 per cent turnover in personnel. Rapid innovation is apt to be frustrated unless there are receptive personnel in key positions.

[2] For an overview of recent work in governmental service systems, see A. W. Drake, R. L. Keeney and P. M. Morse, *Analysis of Public Systems*, MIT Press, Cambridge, Mass., 1972.

[3] See for example, the excellent analysis of two large scale efforts in the area of urban planning by G. D. Brewer, *Politicians, Bureaucrats and the Consultant. A Critique of Urban Problem Solving*, Basic Books, New York, 1973.

Most often, implementation must be viewed as a multiyear process, making governmental services distinct from their industrial counterparts.

In our research project, Prof. Robert Fogelson (a historian in the Department of Urban Studies and Planning, M.I.T.) is analyzing the process of innovation during the last 70 years in the United States. He is focusing on the response of police personnel and their *de facto* unions to attempted innovations, both technological and organizational. This effort is aimed at providing guidance to those performing the analytical modeling regarding the projected response of police personnel and their unions to innovations that may evolve from the more narrow technical work. Fogelson's efforts should shed light on constraints that otherwise may have remained hidden until after attempted implementations, and they should suggest aspects of various innovations that police unions may find attractive (as well as unattractive).

4. Resistance to Outside Technical Assistance. Until recently, there has been no provision or motivation for agency administrators to call upon outside experts or consultants for assistance in helping analyze an operational or planning problem. In police departments, for instance, several well-known police administrators have stated that outsiders have little to contribute because they have had no on-the-beat experience. This attitude in a manufacturing firm would require all executives to start as assembly-line workers. Until the recent initiation of Federal funding programs, it has precluded successful interaction of professional problem solvers and agency administrators. Moreover, in those few circumstances in which such interaction is funded locally, the 1 or 2 per cent of the budget for outside technical assistance often receives the most careful scrutiny and subsequently the sharpest cuts, apparently neglecting the fact that 90 per cent or more of the total budget is consumed directly by employee salaries and fringe benefits. Thus, the operational problems of these agencies only recently have become known to those other than agency employees.

This situation has contributed to the delay of urban public safety services in modifying and implementing various modern technological innovations that could markedly improve performance and productivity. One example is the computer. Urban public safety systems (and many other governmental service systems) are years behind their industrial counterparts in incorporating the computer's capabilities in day-to-day planning and decision making. Prof. Kent Colton (an urban planner at M.I.T.) is continuing a multiyear survey of more than 150 police departments to determine what factors have led to delay in computer implementation and which departments have the internal capabilities to be intelligent consumers of computer services. He is also working to project the use of computers in such new application areas as resource allocation, command and control systems, and automatic vehicle monitoring systems.

5. Operational Complexity. The physics that governs the operational behavior of urban public safety systems is complex and, at this time, poorly understood. This lack is due to several circumstances. The exact times and locations of demands for services cannot be determined precisely in advance. The time required to service an incident is likewise unpredictable. There are many priority or importance levels of requests for service. There are often many cooperating emergency response units within a region, making the number of highly interdependent status and performance variables quite large. There are needs to have point-referenced performance measures (e.g., average travel time to an emergency at a particular address) as well as area-referenced performance measures (e.g., average region-wide travel time). Each of these factors adds complexity in the operational analysis of these systems. Thus the understanding of the physical behavior of urban public safety systems is still in its embryonic stages.

The simulation model to be discussed later in this paper represents one tool for studying the physics of these systems. Others now are being developed as part of our NSF-RANN efforts.[4]

Undoubtedly, there are still other factors one might cite when discussing the difficulties of implementing changes based on methods of operations research and related types of analysis. As illustrated above, the approach used in our NSF-RANN research program includes the identification of social, political and bureaucratic factors that are at least as important as the technical results of the analysis, and the study of these with an eye toward instilling innovation as a common practice within these systems. In addition, as new quantitative tools are developed in the course of the research, we plan to document each quantitative model or procedure with an easily understood case study, selected from and with the concurrence of one of several local cooperating public safety agencies. To the maximum extent possible, we draw on the expertise of one or more of the administrators of the selected agency or agencies to obtain the following:

1. A more realistic case study, including often ill-defined legal, political and social constraints.

2. A sense of the limitations of the particular quantitative method under study.

3. The understanding and cooperation of the agency.

4. It is hoped—the commitment of the agency to implement the method at least on a trial basis.

[4] See for example: R. C. Larson, "A Hypercube Queuing Model for Facility Location and Redistricting in Urban Emergency Services," *Journal of Computers and Operations Research,* Vol. 1, No. 1, 1974; R. C. Larson, "Illustrative Police Sector Redesign in District 4 in Boston," *Urban Analysis,* Vol. 2, No. 2, 1974; G. L. Campbell, *A Spatially Distributed Queuing Model for Police Patrol Sector Design,* Technical Report No. 75, MIT Operations Research Center, Cambridge, Mass., 1972; J. P. Jarvis, *Optimal Dispatch Policies for Urban Server Systems,* Report TR-02-73, Innovative Resource Planning in Urban Public Safety Systems, Laboratory of Architecture and Planning, Massachusetts Institute of Technology, Cambridge, Mass., 1973.

The Relevant Quantitative Tools

Before one of the recently developed quantitative tools is detailed, the mathematical modeling methods that are most relevant are discussed briefly. These methods are presented in a new M.I.T. graduate course. "Analysis of Urban Service Systems," which has evolved from the recent NSF public systems work at the M.I.T. Operations Research Center.[5]

Geometrical Probability—One relevant tool is geometrical probability, a branch of applied probability that has seen successful application in astronomy, atomic physics, biology, crystallography, sampling theory and virology.[6] However, the techniques of geometrical probability have not been widely applied to urban public safety systems, probably because most previous applications have been in areas far removed from urban problems. Yet geometrical probability concepts are particularly relevant in examining problems involving spatial interrelationships between response units of urban public safety services and demands for their services. For instance, given the spatial distribution of police patrol units and incidents throughout the city, a police administrator can predict neighborhoods that receive inadequate coverage in anticipation of various types of emergencies that might arise, the workloads of police units in each of the areas or the likelihood that the *k*th closest unit would require more than *t* minutes to travel to the scene. Geometrical probability techniques are important in planning situations in which an administrator examines how alternative numbers and positionings of units in the field affect the performance of the system.

Generally speaking, the models developed that use geometrical probability methods have the advantage of indicating first-order interrelationships among parameters. They thereby improve intuition and provide guidance to administrators who may have to incorporate other nonquantifiable issues into their decision making. Thus, these models indicate the general nature of the effect of adding more units in a certain region, installing a high-resolution car locator system, or designating particular units as specialists in certain types of incidents. Rather than yielding precise numerical "answers" as one finds with a complex optimization model, these models typically offer a range of policy options in which the user can incorporate political and legal constraints perhaps not included in the models. Thus, the methods provide a general tool for analyzing operational questions, but they do not purport to provide precise answers to the problems.

Multiserver Queuing Theory—A second class of relevant tools derives from multiserver queuing theory. A queuing situation evolves when a population places excessive demands on a limited-capacity service system. For instance, a city's population generates the need for ambulance service. If too much service is required in too short a time period, certain requests for ambulance service may have to wait in queue until ambulances become available to respond. An administrator would want to examine the trade-offs between the costs of additional ambulances and the delays incurred with different numbers of ambulances. This type of question can be approached from a queuing theory point of view. The important new feature in applying queuing ideas to urban public safety services is the close interrelationship between spatial positions of servers and demands, and the time sequence of arrival times and service completions. Such spatial and temporal interrelationships are relatively unexplored in queuing theory and are providing an important area for current research.

Again, queuing models are useful for obtaining first-order interrelationships among parameters applied to urban safety services. They already have provided insights about the placing of boundaries between ambulance garages, the location of facilities, the number of patrol units needed to provide an acceptable level of service, and the amount of cross-district dispatching that a system is likely to incur.[7]

Networks and Algorithms

In recent years interest has been focused on network problems and algorithms based on mathematical programming techniques. The applications of these techniques to the urban public safety systems area include problems of design of transportation, communication, distribution, and collection systems. Other applications are more

[5] See R. C. Larson, "A New MIT Graduate Course: Analysis of Urban Service Systems." *Urban Analysis,* Vol. 1, No. 1, 1972.

[6] See M. G. Kendall and P. A. P. Moran. *Geometrical Probability.* Charles Griffin and Co., London, 1963.

[7] See for example, Drake, Keeney, and Morse, *op. cit.,* especially Chapters 7, 8, and 10.

unexpected; design of work schedules, work force size problems, design of hiring strategies, and optimal location of service facilities are among these.[8]

Simulation—When complex combinations of policy alternatives are being contemplated in an actual urban environment, analytical models are used first to achieve certain insights and to indicate important unresolved problems; then simulation models are used to examine the policy alternatives in detail.

Simulation of urban public safety systems presents many new problems not ordinarily faced in more usual situations. To be effective, such a simulation must be structured to reflect fully the spatial relationships inherent in the operations, as well as the sequential time nature of events common to many systems. The spatial organization of the simulation must be sufficiently general so that one can readily examine problems involving partitioning of a city into various service districts (e.g., ambulance or hospital districts, police patrol sectors), spatial distribution of response units and incidents within districts, and determination of preferable dispatching strategies.

A Simulation of Urban Police Patrol and Dispatching

As part of our NSF-RANN work we are developing a number of quantitatively oriented tools to assist decision making based on the methods outlined above. Some are just now at the point of inception, whereas others are well down the road toward implementation in operating agencies. In the following paragraphs we describe a simulation model of police patrol and dispatching that falls in the latter category. It was developed under NSF support at MIT several years ago and now is being implemented in several police departments in the United States and Canada. Continued refinement and analysis of implementation results is an important part of our NSF-RANN work.

The simulation model is constructed to allow users to replicate to a very great extent the actual dispatch and patrol operations of most urban police departments. It provides thereby a tool to assist in answering a wide range of allocation questions. Police administrators should find simulation models valuable for the following purposes:

1. They facilitate detailed investigations of operations throughout the city (or part of the city).
2. They provide a consistent framework for estimating the value of new technologies.
3. They serve as training tools to increase awareness of the system interactions and consequences resulting from everyday policy decisions.
4. They suggest new criteria for monitoring and evaluating actual operating systems.

Earlier work by Colton[9] reporting survey results from approximately 500 police departments revealed that police view the use of computers for resource allocation as the single most important application of computers in the coming years. Simulation models and other analytical tools should play an important role in this work.

Overall Model Structure—This section will outline the structure of the model developed by the author and its use in an on-line interactive mode. The simulation works in the following way. Incidents are generated throughout the city and distributed randomly in time and space according to observed statistical patterns. Each incident has an associated priority number, the lower numbers designating the more important incidents. For instance, a Priority 1 incident would be officer-in-trouble, felony-in-progress or seriously injured person; a priority 4 incident could be open fire hydrant, lock-out or parking violation. As each incident becomes known, an attempt is made to assign (dispatch) a patrol unit to the scene of the incident. In attempting this assignment, the computer is programmed to duplicate as closely as possible the decision-making logic of an actual police dispatcher. In certain cases this assignment cannot be performed because the congestion level of the force is too high; then, the incident report (which might in actuality be a complaint ticket) joins a queue of waiting reports. The queue is depleted as patrol units become available.

The model is designed to study two general classes of administrative policies—the patrol deployment strategy, and the dispatch and reassignment policy.

The patrol deployment strategy determines the total number of patrol units, whether units are assigned to nonoverlapping sectors, which sectors constitute a geographical command and which areas are more heavily patrolled than others. The dispatch and reassignment policy specifies the set of decision rules the dispatcher follows when attempting to assign a patrol unit to a reported incident. Included in the dispatch policy are the priority structure, rules about cross-precinct dispatching, the queue discipline and so forth.

The model tabulates several important measures of operational effectiveness. These include statistics on dispatcher queue length, patrol travel times, amount of preventive patrol, workloads of individual patrol units, the amount of intersector dispatches, and others.

The simulation program is organized to reflect the spatial relationships inherent in patrol operations, as well as the sequential time nature of events which is common to all simulations. First, the spatial or geographical structure is discussed, then, the time sequence of events.

Geographical Structure—The city, of arbitrary shape, is partitioned into a set of "geographical atoms." Each atom is a polygon of arbitrary shape and size. The atoms are sufficiently small so that any probability density function can be considered uniform over the atom. Such functions depict, for instance, the positions of reported incidents. This partitioning does not restrict accuracy of results, because the atoms can be arbitrarily small.

A patrol unit's *sector* is a collection of atoms. The atoms in the collection need not be contiguous (spatially) or consecutive (in the numerical ordering of atoms). In general, each atom may belong to any number of patrol sectors, which are overlapping.

A patrol command (for instance, precinct, district, or division) is also a collection of atoms. Each sector must be fully contained within a command.

Time Sequence of Events—The simulation is an *event-paced* model. That is, once a certain set of operations associated with one event is completed, the program determines the next event that occurs and updates a simulation clock by adding, to the present time, the time until the next event. The program then proceeds with the set of operations associated with that event. Once the clock reaches some maximum time (T_{max}), the simulation is terminated and summary statistics are tabulated and printed. One completed run of the simulation entails inputting data, initializing simulation status variables, executing the program for an equivalent time T_{max} and printing the summary statistics.

The details of the various dispatching algorithms or patrol deployment policies are not included here. But a brief discussion of the important parameters at each point in the simulation is provided.

The main type of event that occurs is a reported incident or a "call for police service." The times of occurrence of calls are generated as in a Poisson process with rate parameter LAMBDA (equal to the average number of calls per hour). The greater the value of LAMBDA, the more likely it is that the system will incur congestion (saturation) of resources. The location of the call is determined from historical patterns which indicate the fraction of calls that originate from each atom; given the atom of the call, its spatial location within the atom is assumed to be uniformly distributed. The priority of the call is determined from historical data which may vary by atom.

Once the position and priority of the incident are known, the program executes a DISPATCH algorithm, which attempts to assign a patrol unit to the incident. This algorithm is governed by the *dispatch policy* specified by the user. One component of the dispatch policy specifies the geographical area from which a unit may be dispatched:

Option 1: Only assign a unit whose patrol sector includes the geographical atom containing the incident (a sector policy).

Option 2: Only assign a unit whose precinct or district designation is the same as that of the incident (a precinct or district policy).

Option 3: Only assign a unit whose division designation is the same as that of the incident (a division policy). A division consists of several precincts or districts.

The particular option on a given run usually is specified at the start of the run, although the user may choose to use the interactive feature to alter the dispatch policy during the course of a run.

Given that a patrol unit is within the correct geographical area for a particular incident, the algorithm then determines whether the unit is considered eligible for dispatch to this incident. This determination focuses on estimated travel time to the incident, the priority of the incident and the current activity of the patrol unit. In general, the user may specify a dispatch policy that allows very important incidents to preempt (interrupt) patrol units servicing incidents of lesser importance. In addition, the importance of preventive patrol may vary with each unit, thereby giving the user the capability of assuring at least some minimal level of continuous preventive patrol.

If no unit is found eligible for dispatch, the reported incident is inserted at the end of a queue of other unserviced incidents. There may be separate queues for each command and each priority level.

If at least one unit satisfies the eligibility

[8] See C. Revelle, D. Marks and J. Liebman, "An Analysis of Private and Public Sector Location Models." *Management Science: Theory*, Vol. 16, 1970, pp. 692-707. Also N. B. Heller, *Proportional Rotating Schedules.* Ph.D. Dissertation, University of Pennsylvania; Philadelphia, Pa., 1969.

[9] K. Colton, "Police and Computers: The Use, Acceptance and Impact of Automation." *1972 Municipal Year Book*, International City Management Association, 1972.

conditions, it is selected for dispatch according to a prespecified criterion such as minimal expected travel time. The assigned unit's priority status and position are changed accordingly.

A second major type of event occurs when a patrol unit completes servicing an incident. A REASSIGNMENT algorithm then is executed that either reassigns the returning unit to an unserviced incident or returns the unit to preventive patrol. The eligibility conditions regarding priorities, travel distances, and geographical areas are necessary to specify a dispatch policy. They also constitute an integral part of the reassignment policy. In addition, it is necessary to specify how one unserviced incident is given preference over another. This part of the reassignment policy, called the *reassignment preference policy*, parallels the *queue discipline* in ordinary queuing systems.

Location Estimation—If not all available position information is used or if the unit is performing preventive patrol, the method of estimation of patrol unit position must be specified. Three options are available. One simulates the information provided by an *automatic car locator system*.[10] The other two simulate estimation guessing procedures that are commonly found today in most police operations.

Simulation Variables—The simulation program can tabulate statistics on any algebraically defined variable. The variables that have been recorded most often in the author's studies are:

1. Total time required to service an incident, that is, travel time plus time at the scene.
2. Workload of each patrol unit, measured in total job assignments and in time spent on jobs.
3. Fraction of services preempted.
4. Amount of preventive patrol.
5. Travel time of a unit to reach the scene of the incident.
6. Dispatcher queue length.
7. Dispatcher queue wait.
8. The number of intersector dispatches.
9. The fraction of dispatcher and/or reassignment decisions for which the car position was *estimated*, rather than known exactly.
10. The fraction of dispatch decisions which were nonoptimal, in the sense that there was at least one available unit closer to the scene of the incident.
11. The extra distance traveled as the result of a nonoptimal dispatch assignment.

As will be discussed below, each variable may be tabulated at any one of several levels of aggregation.

On-Line Interactive Capabilities—Following the initial creation of the model at MIT, a number of individuals and organizations have been modifying and developing the model for various implementation purposes. Here we discuss one such effort by R. Couper, K. Vogel and J. Williamson[11] which has been devoted to implementing an easy-to-use on-line Input/Output package with the simulation. This effort has resulted in a program that is usable readily by someone without detailed knowledge of computer operation, the simulation logic, or statistics. (Several other simulation development efforts are outlined in the next section.)

The core of the Input/Output package is a sequential tree structure, which presents to the user the options available to him. If the user expresses interest in a particular option, details of use are printed out, the level of which is determined by the responses of the user. Default options are standard, so that if the user does not know what to do at a particular point, a simple carriage return yields additional helpful information. A sample Input/Output session is depicted in Table 1.

TABLE I. **Sample I/O Session**

Enter districts to be simulated (or enter "all").
15 (Italics indicate user's instructions.)

Enter districts you wish to modify.
none

Do you want to change any variables?
yes

Simulation Variables and Their Values

1. Length of simulation run = 2.00 hours
2. Number of calls per hour =

Distr.	1	2	3	4	5	6	7	11	13	14	15
	8	17	8	12	5	6	4	10	5	5	3

3. Vehicle selection method = Strict center of mass
4. Service time at scene and vehicle response speed

Priority	1	2	3	4
Serv. time (in min.)	33	33	33	33
Resp. speed (in mph)	15	12	12	10

5. Type of simulation output=City
6. More detailed information

Enter number(s) of those to be changed
1, 3, 5

1. Enter the length of the simulation in hours=
20

3. There are 3 vehicle selection procedures, they are=
   1. Modified center of mass
   2. Strict center of mass
   3. The resolution of a vehicle location system

Please enter the number of your choice=
2

5. Do you want city-wide or district simulation output?
district

[10] See R. C. Larson, *Urban Police Patrol Analysis*, MIT Press, Cambridge, Mass., 1972, Chapter 7, for more details of simulating automatic car locator systems.

[11] R. Couper, K. Vogel and J. Williamson. *Final Report on the Computer Simulation of the Boston Police Patrol Forces.* Urban Sciences, Inc., Wellesley, Mass., 1972.

Once the initial input/output session is completed, the user has specified the following: the particular geographical data base he wishes to employ (these data are usually stored on disk), the patrol deployment policy (a standard one also is stored on disk), the dispatch procedures, the method of car location estimation, the length of the run and whether he desires to trace the simulation (and possibly interact with it) while in progress.

Following completion of the simulation, a LEVEL 1 output is printed. A sample is shown in Table II.

Table II. **Sample LEVEL 1 Output**

STATISTICAL SUMMARIES—DISTRICT NO. 15

The average patrol unit spent 34.21% of its time servicing calls.

Average response time to high-priority calls was 6.40 minutes.

Average response time to low-priority calls was 7.27 minutes.

Average travel time was 3.19 minutes.

Average total job time was 34.59 minutes.

This contains a small number of highly aggregated statistics describing the run: average travel time, average total response time (including queuing delay), average workloads, etc. The LEVEL 1 output contains no statistical jargon (for instance, variance or sample size) and no program variables. It is self-contained and self-explanatory. LEVEL 1 output has been found to be quite useful for introducing police planners and administrators to the capabilities of the simulation and for quickly eliminating runs with obviously poor performance characteristics.

At this point the user may request LEVEL 2 output. A sample is shown in Table III. As can be seen, this level is less aggregated and provides average values of many variables by priority level. It is expected that a sizable number of users will find the information presented in LEVEL 2 adequate for certain high-level planning and decision-making problems, such as determining overall manning levels.

Table III. **Sample LEVEL 2 Output**

Do you want to see LEVEL 2 statistics?
yes

Statistical summaries—District No. 15

An average of 34.21% of time of all units was spent servicing calls.

The following units were substantially below this figure:

Unit No.	Unit Type	%
4	Wagon	0.00

The following units were substantially above this figure:

Unit No.	Unit Type	%
1	Sector Car	79.14

Average times for each type of call were as follows:

(Stated in Min.)

Priority	Dispatch Delay	Travel Time	Response Time
1	0.00	1.60	1.60
2	5.06	3.40	8.46
3	0.00	0.00	0.00
4	3.72	3.55	7.27
	3.62	3.19	6.81

The average travel time was 3.19 minutes with regular spread.

10.53% of calls incurred a queuing delay due to car unavailability.

0.32=aver. extra miles travel due to not dispatching closest car.

Average total job time (travel time + time at scene) by priority was:

1. 77.54 minutes
2. 37.45 minutes
3. 0.00 minutes
4. 18.05 minutes

The average queue length for each type of call was:

1. 0.00
2. 0.51
3. 0.00
4. 0.43

The maximum delay in queue for each type of call was:

1. 0.00 minutes
2. 35.39 minutes
3. 0.00 minutes
4. 33.46 minutes

If the user desires even more detail, he may now request portions of a LEVEL 3 output. A sample is shown in Table IV. As one can see, this

Table IV. **Sample LEVEL 3 Output**

Do you want to see LEVEL 3 statistics?

yes

District Summary

Parameter	Over-all Aver-age	Stand-ard Devi-ation	Maxi-mum Value
1. Workload (%)	34.2	28.6	79.1
2. Response time (minutes)	6.8	10.9	39.8
3. Travel time (minutes)	3.2	2.0	10.5
4. Extra distance (miles)	0.3	0.4	1.2
5. Total job time (minutes)	34.6	49.2	227.3
6. Number of calls pre-empted for higher priority	= 0 (0%)		
7. Number of calls assigned to unit on preventive patrol	=17 (89%)		
8. Number of calls assigned to unit assigned to sector	=17 (89%)		
9. Number of calls assigned to cars other than closest	= 7 (37%)		

For which parameter do you want a further break-down?

1

Workload by Priority

Patrol Unit	1	2	3	4	Total
1	47.4%	17.6%	0.0%	14.2%	79.1%
2	0.4%	17.3%	0.0%	7.1%	24.8%
3	0.7%	19.7%	0.0%	12.5%	32.9%
4	0.0%	0.0%	0.0%	0.0%	0.0%

Do you want more detail for any other parameters?

yes

For which parameter do you want further break-down?

7

By priority?

no

For which units?

all

Calls Assigned to Unit on Preventive Patrol

Patrol Unit	No. Calls	Per Cent
1	6	100.0%
2	6	85.7%
3	5	83.3%
4	0	0.0%

level presents many detailed statistics and can be of great assistance in very fine-grain planning problems—for instance, sector design. It is expected that very experienced users usually will demand LEVEL 3 output before making decisions affecting actual operating procedures in the field or at the dispatcher's position.

Regarding the other on-line capabilities, the TRACE option, which prints out the details of each call, assignment and reassignment in real time, assists new users in learning the operation of the model and in developing a good intuition for system operation. The TRACE option potentially can be used for training dispatchers in new dispatching procedures. In this mode of operation, the computer would request the user to make the dispatch or reassignment decision at the appropriate times, and the standard DISPATCH and REASSIGNMENT algorithms would be by-passed. Once the dispatcher-user settles on a particular strategy he wishes to test in detail, he can stop the TRACE, input the control parameters describing his strategy and run the model for a sufficiently long time to obtain reliable statistics.

Implementation

At the time of this writing (January 1974), the simulation model described above and several other models being developed as part of our NSF-RANN work are being implemented or are planned for implementation in the following cities: Boston; New York; Washington, D. C.; Quincy, Mass.; Newark, N. J.; Cambridge, Mass.; and Lowell, Mass.

The work with Boston, Cambridge and Quincy is being supported as part of our NSF-RANN activity. It focuses primarily on various analytical models for sector design, dispatch selections, and preventive patrol allocation. The remainder of the implementation work, supported by various other agencies, utilizes the simulation model described above and, in one case, a resource allocation algorithm,[12] both of which were developed at MIT several years ago under NSF support. Their technical details now appear in the open literature.

The following paragraphs outline a portion of this implementation activity, focusing first on the work in the greater Boston area. Much of this work utilizes the so-called hypercube queuing model,[13] which currently is being developed and extended under NSF-RANN support.

[12] See R. C. Larson, *Urban Police Patrol Analysis* (note 10), Chapter 5.

[13] See, for example, R. C. Larson, *A Hypercube Queuing Model, op. cit.*; R. C. Larson, *Illustrative Police Redesign;* G. L. Campbell, *op. cit.;* and J. P. Jarvis, *op. cit.*

Boston—The Boston Police Department announced Sept. 18, 1973, the largest change it had ever made in its policies of patrol manpower allocation. The total number of cars on the street was increased from a daily average of 179 to 261, an increase of 46 per cent. Commissioner Robert J. diGrazia announced that the department's new "Maximum Patrol and Response Plan" was the result of a five-month study by the Police Command Staff, the Bureau of Field Services, field personnel and consultants. During July, a case study applying the hypercube queuing model to District 4 in Boston was done by the author in response to a request from the Police Command Staff. Copies were distributed to the Boston task force. The initial focus was on District 4 because that district contained nearly an entire spectrum of neighborhood characteristics to be found elsewhere in Boston. Thus, it was felt that if the plan worked in District 4, it would also work in the other Boston police districts.

Several quantitatively based objectives provided the goals of the reallocation plan:

1. Provide immediate response (i.e., no queue delay at the dispatcher's position due to patrol unit unavailabilities) for at least 95 per cent of all calls.
2. Approximately equalize workload per car.
3. Provide about 50 per cent of street time for patrol.

The District 4 Commander, Deputy Superintendent Joseph M. Jordan, reported that 93 per cent of calls were answered immediately during a trial implementation in District 4, using numbers of patrol units derived from queuing analysis.

Workloads were distributed very unevenly prior to implementation of the new plan. For instance, cars in District 7 (East Boston) were answering calls for about three hours during the day, five hours at night and two hours in the early morning shift. However, cars in District 11 (Dorchester) were answering calls for more than six hours during the day, virtually all of the time during the night shift, and more than seven hours during the early morning shift.

Furthermore, District 11 cars were often unable to respond to all of the calls during the night shift. The new plan attempts to give at least four hours to each car in each shift for preventive patrol activities. It significantly reduces such marked workload inequities.

Examining the computational results of the case study, the Task Force felt additional workload and travel time inequities due to geographical factors could be significantly reduced by formalizing a procedure for *inter-district* dispatching. Thus, a sector which may have been "outlying" in one district now may assume a new central role if its patrol unit is dispatched to calls in an adjacent district. The converse is true for units in the adjacent district.

The extra manpower required to implement the new Boston allocation policy was drawn from sworn police personnel performing clerical functions. The Task Force found that many clerical functions were unnecessary or could be handled by other agencies. Many non-vital clerical functions were eliminated, including such functions as duplicating at the district level records available at headquarters. New organizations were drawn for district personnel and new procedures developed to speed the remaining paper work, thereby making policemen who previously performed clerical functions available for street duty.

Cambridge and Quincy, Massachusetts—Use of the model by the Cambridge and Quincy Police Departments still is at a more preliminary stage. The directors of planning and research of both departments are now collecting the data required to operate the model. Both plan to perform the sector-redesign iterations themselves, using the computer programs developed at MIT.

The Cambridge sector plan has not been redesigned for more than 20 years, and there is evidence of marked inequities in patrol workloads. An officer assigned to the most centrally located sector has recently complained to planning and research staff about the operation of his police car radio. He was asked, "What is the matter? Doesn't it work?" He responded, "Yes, it works—that's the problem. Every time I'm free, I'm being sent to someplace else in Cambridge on another assignment." Naturally, the Cambridge Director of Police Planning and Research hopes to reduce this workload burden by exploring different sector design options with the aid of the model.

The Quincy Police Department is performing a broad-based operational analysis under a grant for innovative planning, supported by the Massachusetts Governor's Public Safety Committee. (This committee is the state planning agency in Massachusetts for the Law Enforcement Assistance Administration of the U.S. Department of Justice.) Part of this activity requires use of analytical and simulation models of police activity to improve planning and day-to-day decision making. The City of Quincy, situated on Quincy Bay, has many natural and man-made barriers to travel, thereby limiting the number of feasible alternative sector designs. The Director of Planning and Research is therefore particularly interested in learning the magnitudes of the effects on performance discussed here in a Boston context.

Both the Cambridge and Quincy implementation experiences will be documented as reports of our NSF-RANN project.

Washington, D. C.—An off-line version of the simulation model is being created and implemented for the Washington, D. C., Metropolitan Police Department under the technical guidance of Mathematica, Inc. and with the support of the Law Enforcement Assistance Administration.[14] Here the city's geographical structure is modeled as a set of discrete points, rather than polygons, each point corresponding to one city (surveyor) block. For Washington, D. C. this represents approximately 4,000 points, or sufficiently fine-grain detail to make the model useful for sector redesigns for the 138 scout cars distributed throughout the city. The selection of a point geography was based on detailed block-level statistics available for Washington, D. C., and on the fact that an off-line model need not produce rapid turnaround times (in the same sense as an on-line real time model). This effort began in January 1972, and is reported in periodical publications of Mathematica, Inc. and the Washington, D. C. Metropolitan Police Department.

New York—The New York City Police Department in August 1972 contracted with the New York City-Rand Institute to adopt the on-line simulation and a resource allocation algorithm to the special requirements of New York City and to implement these tools for analysis of the entire patrol force (distributed throughout 75 precincts in over 700 regular radio-dispatchable patrol cars, plus special-assignment cars and radio-dispatchable foot patrolmen). The Department eventually hopes to provide each precinct commander with a readily understandable set of on-line decision tools, with easy terminal access from each of the 75 precinct station houses. Thus, it is hoped that these tools will be used for short term decentralized decision making, as well as for longer term centralized resource allocation, and planning and research. As of the present writing, this project still is in progress, and draft reports are available from the New York City-Rand Institute.

National Research Council of Canada—During the last two years, F. R. Lipsett and J. Arnold of the Radio and Electrical Engineering Division of the National Research Council of Canada have reprogrammed the version of the simulation model detailed in Larson (1969) to adapt the programs to their computing system. Their work is currently in progress, aimed at determining the potential usefulness of simulations to both small and large police forces. They have successfully simulated a cooperating police force near Ottawa (Gloucester Township) which operates with five sectors and five patrol cars over a 125 square mile region. Their current work, now at the data collection stage, is with the Ottawa Police Department. Documentation should be available early in 1975.

[14] See H. F. Miller and B. A. Knoppers, "A Computer Simulation of Police Dispatching and Patrol Functions." Paper presented at the 1972 International Symposium on Criminal Justice, Information and Statistics Systems, New Orleans, La., 1972.

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