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ABSTRACT

An urban emergency service system provides mobile units (vehicles) to respond to requests for service which can occur at any time and any place throughout a city. This paper describes the common characteristics and operational problems of these systems and surveys the various methods, both traditional and recently-developed, which may be used for allocating their units. Aspects of allocation policy discussed include (1) determining the number of units to have on duty, (2) locating the units, (3) designing their response areas or patrol areas, (4) relocating units, and (5) planning preventive-patrol patterns for police cars.

Typical policy changes which may be suggested by the use of quantitative allocation models include selective queuing of low priority calls, varying the number of units on duty (and their locations) by time of day, dispatching units other than the closest ones to certain incidents, relocating units as unavailabilities begin to develop, and assigning police cars to overlapping patrol sectors. As a result of making such changes, it is often possible to reduce queuing and travel-time delays, improve the balance of workload among units, and enhance the amount of preventive patrol where needed.

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I. INTRODUCTION

Urban police and fire departments, emergency ambulance services, and similar urban emergency service systems comprise an important class of governmental service agencies that until recently has not benefited from systematic analyses of operational problems. These systems operate in a complicated environment that includes temporally and spatially varying demand patterns, both explicit and implicit administrative, legal, and political constraints, and often ill-defined mixtures of objectives.

Our purpose in this paper is to review those operational problems of these agencies which are related to the deployment of their vehicles and to report current progress on mathematical modeling approaches to these problems. One cannot expect to find universally acceptable solutions -- the agencies and their problems differ too much from city to city. Instead, we discuss the methods which are available, the extent of improvement that can be achieved as a result of quantitative study, and the type of solutions that can be obtained. Details of the models described here may be found in the cited references.

Agency administrators faced with the need to provide remedies for service delays and overworked personnel can use the methods described here in two ways. First, they can improve the deployment of their existing personnel. This is desirable even if there is a possibility of hiring more personnel, since the cost of even a single additional emergency unit is usually large enough to justify whatever analysis may be required to bring about the enhanced performance level without the added unit.¹ Second, they can determine the number of men required to meet specified objectives in the future. This

application is recommended for budgeting purposes in planning and administration texts [33,67], since personnel costs constitute as much as 90 to 98 percent of the budget of an emergency service.

We are considering here, as an urban emergency service, any system having the following properties:

- o Incidents occur throughout the city which give rise to requests or calls for service (e.g., fire alarms, crime victim assists); the times and places at which these incidents occur cannot be specifically predicted in advance.
- o In response to each call, one or more emergency service units (vehicles) are dispatched to the scene of the incident.
- o The rapidity with which the units arrive at the scene has some bearing on the actual or perceived quality of the service.

In addition to such examples as fire engine and ladder trucks, police patrol cars, and ambulances, emergency service units include certain tow trucks, bomb disposal units, and emergency repair trucks for gas, electric and water services.

Although all urban emergency service systems share the above characteristics, they may differ in certain significant details:

First, some emergency units are ordinarily found at fixed locations at the time of dispatch. Others, such as police patrol cars, are mobile. This distinction is important for both administrative and analytical purposes. For instance, in principle it is possible to vary the location, size and shape of police patrol sectors at will, whereas the response areas of fire

units must be designed in relation to the (fixed) locations of the fire stations. Also, the dispatch strategy for mobile units can often be improved by a variety of location-estimation techniques which are not needed if units are positioned at known locations. For instance, a police dispatcher could improve his decisions by querying the cars as to their locations² or using information from an automatic car locator system.

The distinction between mobile and fixed-location units begins to break down during periods of high demand. At such times the units may be dispatched directly from one incident to the next, or they may be dispatched while en route from a previous incident to their home locations.³ Under such conditions, system operation is not very sensitive to the distribution of initial locations, either fixed or mobile.

Second, emergency services differ in their ability to determine the urgency of their calls in advance. For example, false alarms of fire, while not urgent, cannot often be identified with assurance.⁴ On the other hand, a telephone call to the police reporting a past burglary can be identified as not requiring the immediate response of a patrol car.⁵ The fraction of non-urgent calls to an emergency service ranges from around 10 percent in the case of ambulances [56] to 40 percent for fire alarms in New York to 75 percent for police departments [34].

The ability of an emergency service to distinguish the priorities of its calls determines the options open to the dispatcher under near-saturation conditions. If a call can be identified as not urgent, the dispatcher may decide not to send any units, or he may hold the call in queue to await the availability of a unit near the scene; he may even place a call in queue when some units are still available, thereby protecting his ability to dispatch units to future high-priority incidents. However, if the dispatcher cannot recognize the non-urgent calls, he will have to dispatch at least one unit to each incident so that its nature can be determined; no calls can be queued.

Third, for some emergency services the time the units spend between servicing calls is used for another important activity. For example, it is widely believed that routine patrol by police cars acts as a deterrent to certain types of crime [33,53,66]. If police cars spent nearly all their time handling calls for service, the preventive patrol function would suffer. Such an important secondary function is not present in all emergency service systems and should be distinguished from routine internal functions: rest, meals, and training for the men, maintenance of equipment, and preparing written reports.

For units which do have an important secondary function, questions involving the dispatch of units cannot be answered exclusively in terms of the effectiveness of response to emergencies. For example, it may be desirable to place some calls to the police in queue simply to preserve the deterrent patrol. A fire dispatcher would rarely have occasion to make such a decision, since the available fire units are not engaged in any activity which could be judged more important than responding to an alarm.

The allocation (or deployment) policy of an urban emergency service system may be defined as the collection of rules and procedures which determine

- o The total number of units of each type on duty at any one time. (This may differ by time of day, or day of the week, or season of the year.)
- o The number of men assigned to each unit.
- o The location or patrol pattern of each unit.
- o The priority attached to different types of calls, and the circumstances under which calls are queued.
- o The number of units of each type dispatched to each reported incident.

- o The particular units dispatched.
- o The circumstances under which the assigned locations of units are changed. (This operation is variously called relocation, move-up, redeployment, repositioning or reinforcement.) When relocations are required: the number of units relocated, the particular units relocated, and their new locations.

In Sections II-V which follow, four of these topics will be discussed in some detail. We begin with a review of methods for selecting the number of units to have on duty, continue with an approach to selecting which unit to dispatch, and then discuss location-relocation problems and strategies for preventive patrol. Section VI describes other, more general, allocation models and includes some observations about the insights obtained from use of quantitative methods.

II. DETERMINING THE NUMBER OF UNITS TO HAVE ON DUTY IN EACH AREA

The number of units on duty in each area of a city is a major determinant of the performance of the system. We shall discuss two commonly-used methods for selecting the number of units before describing the recently-developed methods based on models.

A. METHODS BASED ON GEOGRAPHY AND LAND USE

Decisions regarding the total number and locations of a city's fixed facilities (e.g., fire houses and police precinct stations) have usually been made solely on the basis of geography and land use patterns. This reliance on geographical factors has been reinforced by geographical standards and regulations which apply to many cities. For example, the Standard Grading Schedule of the American Insurance Association [2] is used in most U.S. cities

(excluding New York) to establish fire insurance rates. As a rule, cities will attempt to meet as many standards in the schedule as possible, so as not to have a lower rating than necessary. But for cities with population over 200,000, the only criteria provided by the Schedule for the number of fire engines and ladders to be located in each part of the city are based exclusively on geography and land use. For certain "high value districts" the Schedule requires every point to be no further than one mile from an engine company and no further than 1.25 miles from a ladder company. Moreover, within 1.5 miles of any point there must be at least 3 engine companies, and within 2 miles at least 2 ladders. These standards may vary slightly from area to area, but for each type of area, the same kind of geographical standard applies.

The main deficiency of geographical standards is that they are meant to be substitutes for standards involving the time between receipt of a call for service and the arrival of emergency units. But this response time depends on many factors aside from geographical ones: the delays incurred in dispatching the units, the speed at which the units can travel, and the probability that particular units will be available. (It is little comfort to know that a fire house is within a mile of your home if the units located at that house would very likely be busy at the time you had a fire.)

Thus, as a general rule, it is not possible to determine whether an adequate number of units are located in each geographical area solely by inspecting a map of the city which shows the home location of each unit.

B. ANOTHER TRADITIONAL APPROACH: WORKLOAD OR HAZARD FORMULAS

Instead of relying on a single factor such as geography, so-called workload or hazard formulas combine in a subjective manner virtually all factors which might be thought relevant for allocating units. They give an appearance of

accuracy because of the large number of factors included.

Perhaps the most well-known such formula was developed for police use by O. W. Wilson in the late 1930's [65,66,67]. Wilson combined indicators of activity (such as number of arrests, number of calls for service of particular types, number of doors and windows to be checked) with other factors (such as number of street miles, number of licensed premises, and number of crimes) to arrive at a "hazard score" for each area. An area's score is computed by taking a weighted sum of the fractions of each of the factors associated with the area. The weight for each factor is a subjective indicator of its relative importance. In applying the formula, the total number of men (or patrol cars) are to be distributed among the areas in direct proportion to their hazard scores.

This procedure often produces unsatisfactory allocations that may have to be "juggled" by hand computations to arrive at a "reasonable" allocation. For instance, the 5 or 10 per cent weighting often given to calls for service may be inadequate to avoid lengthy queue delays in certain areas during periods of high demand, but a higher weighting could affect other properties of the system in undesirable ways. The inherently linear form of a hazard formula precludes description of the highly nonlinear and complex interactions among system components which are often observed in practice. Such a formula also attempts a simple deterministic depiction of a system in which many of the variables are probabilistic. In addition, since some factors (such as arrests) are likely to be highest in sufficiently staffed areas, hazard formulas may have the perverse effect of indicating a need for additional personnel in areas which are already relatively overallocated. But the major difficulty arises in trying to determine how to improve the selection of the subjective weightings, a problem for which there seem to be no underlying principles or guidelines.

C. MODELING METHODS

From a modeling viewpoint urban emergency service systems have two distinctive features: (1) probabilistic variations in demands and service requirements over time and (2) distributions of incidents and response units over the space of the city. The first gives rise to congestion when too much service is demanded in too short a time period and may be examined using queuing theory. The second feature gives rise to travel time distributions, patrol patterns, etc., which can be examined using essentially geometrical considerations. The two types of models are then ordinarily combined, perhaps with additional models of other aspects of performance, to produce an allocation algorithm.

Queuing Models

Since it is characteristic of emergency systems that a person's life or well-being may well depend on the immediate dispatch of a unit to an arriving call, a primary objective of all urban emergency systems is to reduce to a low level the possibility that an urgent call will have to be placed in queue for more than a few seconds. The probabilistic nature of the arrival times and service times of calls is such that one can never guarantee that every call will result in the immediate dispatch of a unit. Thus, the objective of a queuing analysis is to assure that the probability of an important call encountering a queue (or the expected waiting time in queue) is below some specified threshold.

To take a simple hypothetical example, we might imagine a city in which each police patrol car is assigned a geographical response area ("sector" or "beat") in such a way that no other car responds into its area. Then, whenever a given patrol car were busy, all calls from its sector would have to be placed in queue. Given reasonable assumptions, formulas are available for the queuing characteristics of such a single-server system [51,52]. One could use

these formulas to determine the required number of patrol units as follows: A threshold would be selected for the maximum value of the probability of a queue (or average waiting time) to be permitted in any sector; then the sectors would be selected small enough to assure that the threshold is not exceeded. The total number of sectors designed in this way would then determine how many units are needed.

Applications to real emergency services usually require a multi-server queuing model. The N units may be located at one place (e.g., ambulances at a hospital), or they may be distributed throughout a region. In the simplest model, a call is placed in queue only when all vehicles are busy servicing prior calls, all calls have the same priority and exponential service-time distribution, and the arrival process is Poisson. Stevenson [59] has applied the steady-state version of this model to determining how large the number of ambulances in a region must be to assure that the probability of a queue does not exceed a specified threshold. Given an estimate of the arrival rate and other parameters during each time period, an administrator can select a desired threshold probability and determine how many ambulances to have on duty by time period.

The same model has been used in St. Louis for the allocation of police patrol cars [50]. The city is divided into nine patrol districts, and a call is assumed to enter a queue whenever all the cars in its district are busy. For each four-hour time period, the Police Department estimates, using the multi-server queuing model, how many cars will be needed so that at most 15 per cent of each district's calls will experience a queuing delay.⁶

If dispatchers can distinguish the urgent calls from the less important ones, it is useful to introduce priorities into the model. One method, due to Cobham [20], assumes that higher priority calls are served first, but retains the assumptions that one unit responds to each call and that all service times

have the same exponential distribution. Although in most police departments calls are not explicitly assigned priorities according to specified rules, Larson has found this model useful as an approximation to current performance of police dispatchers and as a tool for analysis of the potential benefits of more precise priority schemes [44]. It has the advantage that it places emphasis on reducing the delays which are associated with important calls.

Greater realism could be introduced into this model by (1) permitting each priority level to have different service-time distributions, and (2) allowing the service time to vary with the number of units busy.⁷ But the effort required to design such models cannot be justified unless allocation decisions are found to be sensitive to the current model's assumptions and unless a comparable effort is devoted to collecting and analyzing service-time data.

One refinement of the multi-server queuing model has been found practical, and indeed necessary, for predicting the number of units busy at operations of a fire department. Fire dispatchers typically send several units to each alarm, while the previous models assume that one unit is sent to each incident. In addition, fire units do not all complete service at the same time, since each may have distinct duties to perform.⁸

Chaiken [16] has developed a queuing model which allows for these features of fire operations. In particular, in this model

- o different types of alarms may require different numbers of units of various kinds;
- o the units may arrive singly, or in groups, and they may depart in similar fashion; and
- o the length of time the units are busy at the incident depends on the type of incident.

This is an infinite-server model, so that units required in one region of the city are assumed to be dispatched from there or from another region, if necessary. In applying this model, one specifies, for each region, a threshold for the probability of needing to dispatch units from elsewhere. The model gives the probability that more than n units are busy at once, and one chooses the smallest n for which this probability is under the threshold.

Applying the model in New York City [15], Chaiken found that at low alarm rates (such as occur in the early hours of the morning), the numbers of units needed to meet the requirements of the queuing model are well below the numbers needed to meet simple geographical requirements;⁹ therefore the geographical factors predominate. However, in some parts of the city the queuing model implies a need for more units at times of high alarm rate than would be suggested by geography alone. The same model could be utilized for analyzing operations of other emergency services which dispatch two or more units to certain types of incidents.

The results from these models, as well as from more complex models which incorporate queuing phenomena (e.g., Savas [56]), have a common property: the number of units needed increases with the call rate, but not in direct proportion to the call rate. This simple observation is an illustration of the unsuitability of entering call rates in a linear fashion in workload formulas.

Travel Time Models

Although the typical travel times of four to ten minutes may be dominated by queuing delays during periods of saturation, travel time may comprise the greatest fraction of total response time during normal operating periods [38,45]. Thus, models are required which relate properties of travel time to the number of units on duty, geographical characteristics, arrival rates of calls, and service times at incidents. If all the units serving a region are located at

a single point, changing the number of units has little effect on travel time, as in the "base case" for ambulances studied by Savas [56]. But if the units are spread around the region, travel time-models can replace traditional geographical factors¹⁰ in determining the number of units to have on duty during periods of relatively light demand.

Geometrical models can be used for determining the relationship between travel distance and the spatial distribution pattern of the units. For a model in which units are randomly located, with an average of r units per square mile, Larson [44, p. 323] has found that the right-angle travel distance for the closest unit has a Raleigh distribution with mean approximately $0.63/\sqrt{r}$. Similar inverse square-root laws are found under other assumptions. If the units are not randomly located, but instead are positioned in such a way as to minimize average travel distance [48], the mean is found to be $0.47/\sqrt{r}$. Kolesar and Blum [41] have found similar results for the travel distance of the n th-arriving unit when more than one are dispatched.

Such geometrical models, used in conjunction with empirical data relating travel time to travel distance,¹¹ provide an estimate of the travel-time distribution, given the spatial distribution of the units. If the units can occupy only a small number of specified locations, the travel time for each possible arrangement can be calculated directly from empirical data and estimated arrival rates in subregions, an approach which has been used by Hogg [31]. The entire travel-time distribution should be found, if possible, since ultimately one may be interested in the probability that travel time exceeds a specified limit.

The results from the geometrical models may then be tied with queuing results to determine the travel-time properties of the system, given N total units on duty and the other relevant operating characteristics. The queuing model is used to obtain the probability that n units will be available for

dispatch, and the geometrical model gives the travel-time distribution for this circumstance. Larson [44, p.328] follows such an approach to estimate the average travel time to incidents in a region, given homogeneous travel speeds and random positions of the units. Alternatively, one could assume that the available units are moved, if necessary, so as to occupy the locations which give minimum travel time. Similar methods may be used to estimate measures of travel time other than the mean.

In applying these models to determining how many units to have on duty, two constraints are used. The first specifies a limit on some measure of queuing (the probability of a queue, the probability of needing distant units, or the expected waiting time), and the second sets a limit on an appropriate measure of travel time. It is then possible to determine the smallest number of units meeting both constraints. Such a calculation provides sensible allocations for all regions, whether they experience high call rates or not.

In some circumstances it may be possible to find an empirical relationship between an appropriate measure of travel time and the average density of available units, in which case one can dispense with the geometrical models. Kolesar and Blum [41] have studied the output from a variety of travel-time models, as well as data derived from experiment, and have concluded that if unavailabilities are not too severe the average travel-time \bar{T} is inversely proportional to a power of the average density \bar{r} of available units: $\bar{T} = \alpha / \bar{r}^\beta$. When this approximation holds, the parameters α and β can be determined from data collected in each region, and the resulting formula can be used directly with a queuing model to select the number of units needed.

Methods Using Other Criteria

The simple models described above may not, by themselves, be sufficient to determine the number of units needed. First, for services which engage

in important activities other than response to calls, criteria relating to these activities have to be taken into account.¹² Second, and more fundamentally, easily quantifiable criteria (probability of encountering a queue, average travel time) do not often have a clear relationship to the true performance of the system. For instance, one would like to know the actual benefits which accrue by decreasing response time. Such benefits might be lives saved, stolen goods recovered, property damage averted, etc. Although preliminary research along these lines has been performed [11,27,34], the currently available empirical information is not an adequate foundation for an administrator's use in selecting allocation policies. Thus, at present, one is forced to use available performance measures such as response times. A careful and realistic use of such measures can provide reliable proxies for more fundamental measures, as has been discussed by Carter and Ignall [11].

Given such a necessary reliance on performance measures, an administrator would usually want to employ several simultaneously to arrive at reasonable allocations. In addition to queuing and travel times, he could incorporate factors pertaining to other activities (e.g., preventive patrol) and to administrative matters (e.g., workloads).

Two criteria, travel time and response workload, are analyzed by Carter and Ignall [12] in a queuing model for determining the extent to which an added fire unit provides relief to overworked units in a command. It would be natural to assume that when units are added to a command, the number of responses made by each of its units would decrease, and this may be one of the secondary benefits of adding units which is particularly interesting to an agency administrator. However, in instances where two or more units are ordinarily dispatched to each incident, but fewer are sent when some of them are unavailable, adding a new unit may increase the chances of a full (rather

than partial) response to such an extent that the average number of responses of units in the area actually increases. Thus their model shows that if it is desired to reduce the workloads of units in addition to improving the response time, a greater number of units may be needed than is suggested by simpler models.

Larson [44] has developed a dynamic programming model for allocating police patrol cars to commands (e.g., precincts) which permits police administrators to specify constraints, which may vary by command, on average travel time, the frequency with which cars pass by an arbitrary point while on preventive patrol, the smallest number of units which can be assigned to any one command, and additional criteria related to crime rates or other activities of patrol cars. The algorithm supplies each command with enough patrol units to satisfy all the constraints and then treats the queuing delay as the objective function to be minimized using whatever additional patrol units are available. With limited police resources, it is possible that a specific set of policy objectives is unobtainable. If so, the algorithm indicates the additional number of patrol units required to meet the stated objectives. To allocate the currently available number of units, the algorithm then requires a more modest set of objectives.

When applied in New York City [47], the results suggested that during periods of relative congestion (e.g., Friday and Saturday evenings), average queuing delay could be decreased significantly by diminishing resources in residential commands with relatively light demands and increasing resources in commands which are heavily loaded. Such a redeployment of resources does not noticeably degrade performance in residential commands, since sufficiently many patrol units are retained to satisfy all policy constraints. Yet, average queuing delays in heavily loaded areas can often be reduced from thirty minutes

to less than two or three minutes.

In general, the quality of the allocations which an administrator can expect from any of the models described above depends on how much effort he is willing to have his staff devote to the application. An analyst who is not a member of the concerned agency cannot make an appropriate determination of what constitutes an "excessively long" delay before the arrival of a unit, or how much preventive patrol will be considered adequate, or what level of workload is "too great."

In the case of fire departments, where the various units dispatched to a single incident may arrive at different times, the analyst is not even in a position to know which arrival patterns are "better" than others. However, the field chiefs, who are completely familiar with their department's operating procedures at a fire, can provide valuable information. Through asking a series of questions such as "Would you prefer two fire engines arriving 1.5 minutes after an alarm, or one arriving at the 1-minute mark and one at the 2-minute mark?", it is possible to derive a chief's utility function for arrival times. Work in progress by Keeney [31] to develop such utility functions should make it possible to select the allocation of units so as to maximize a chief's utility of the resulting patterns of arrival times.

It should also be noted that, in regard to any of these methods for determining how many units to have on duty, there may be some difficulty in assigning individuals to shifts or tours of duty which best "fit" the desired assignments. Legal and administrative constraints can make this problem quite difficult. A heuristic approach is discussed by Edie [24]. A more general approach using a computer algorithm has recently been reported by Heller [29].

III. DESIGN OF RESPONSE AREAS

A problem commonly shared by all spatially distributed urban systems is the design of response areas (districts or sectors or beats) that indicate where a particular patrol unit, fire engine, or ambulance is to have primary responsibility. In designing these administrative areas, agency administrators have stated several diverse (often conflicting) objectives: minimization of response time, equalization of workload, demographic homogeneity of each area, and administrative convenience. No single mathematical technique for design of districts is likely to take into account all the relevant factors. Yet, some of the recently-developed models have provided useful insights into the problem.

Traditionally, police planners have been instructed to design patrol sectors as squares, circles, or as straight lines along particular streets. The objective of square or circular designs is to keep at a minimum the time required for the patrol unit to travel to the scene of a reported incident in its sector. For instance, O. W. Wilson states that "...a square beat (sector) permits a maximum quadrilateral area with a minimum distance between any two possible points within it."¹³ [67, p. 228].

However, travel speeds may depend on direction of travel, in which case it will be desirable to design the sector so that the longer sector dimension corresponds to the direction with higher travel speeds. Using quantitative techniques, it is possible to predict the travel time characteristics of any proposed sector design and thereby determine which designs actually do minimize some indicator of travel time.

As an example, consider an urban region in which the streets form a mutually perpendicular grid (e.g., as occurs in central Manhattan and certain other cities), running, say, east-west and north-south. Then, a shortest route of travel for the assigned patrol unit requires the unit to traverse the

total east-west distance, plus the total north-south distance, between the unit's initial position and the position of the incident.¹⁴ Under the simplifying assumption that each patrol unit responds only within its sector, Larson [47] has shown that average intrasector travel time is minimized by designing the sector so that the average time required to travel east-west equals the average north-south travel time. Since it is not unusual to find regions (such as in Manhattan) where the north-south speed is about 4 times as great as the east-west speed, this implies that the sectors should also be 4 times as long in their north-south direction. In this case, such a sector design can be expected to reduce average intrasector travel time by approximately 20% over that obtained by the rule-of-thumb design--square or circular sectors.

Some of these ideas have already been applied by Bottoms, Nilsson, and Olson in the city of Chicago [6]. They have designed a sector plan of the city using rectangular sectors in such a way that the average intrasector travel time does not exceed approximately three minutes.

Certain complications to travel, such as one-way streets and railroad crossings, should be taken into account when estimating travel times. Larson [46] has computed the mean extra distance traveled due to these complications. Although the results indicate that the average travel time does not usually increase very much when such complications are present, a small fraction of responses in a one-way-street grid may require three or more additional minutes for the unit to reach the scene.

INFLUENCE OF INTERSECTOR COOPERATION

When an incident is reported from a response area whose units are busy, most emergency service systems will dispatch an available unit nearby in another response area. Such an arrangement is nearly mandated by queuing considerations, but it introduces subtle complications into the design of re-

sponse districts. In the case of mobile units, it even raises questions about the need for restricting response areas of the units to be nonoverlapping. These consequences of intersector cooperation will be discussed below.

Police Patrol: "flying"

Police administrators are often heard to argue in favor of assigning patrol units to nonoverlapping sectors in order to establish a "sector identity" on the part of the patrol officer. This identity, which derives from patrolling and from citizen contacts made while responding to calls for service, is supposed to cause the officer to feel responsible for public order in his sector. However, given nonoverlapping sectors, one can show by a simple probabilistic argument [45] that the fraction of dispatches which cause a unit to travel outside its own sector is usually equal to or greater than the fraction of time that units in that area are unavailable for dispatch. Thus, if a police department's patrol units are "busy" 40 per cent of the time (a typical value), then at least 40 per cent of all dispatch assignments cause the assigned patrol unit to leave its own patrol sector. For this reason, at least 40 per cent of all citizen contact occurring while responding to calls-for-service takes place in sectors other than the patrol unit's own sector.

The predicted amount of intersector dispatches (called "flying" in some police departments) has been substantially verified both by our own work [45] and by the reports of others [49]. These data showed that the amount of intersector dispatching is never significantly less than the percentage of time unavailable, and it may be significantly more. Intersector dispatches ranged from 37 to 57 per cent of the total.

The extent of flying brings into question not only the philosophy behind nonoverlapping sectors but also a widely popular statistical procedure for computing workloads of police patrol cars. Usually a sector is associated with a "workload" which is proportional to the number of calls for service generated from within the sector. However, it is clear that the number of intersector dispatches may be sufficiently large that one should calculate workloads of units from records of their dispatch assignments and not from the rates of calls for service in individual sectors.

There is one additional property of nonoverlapping sector systems that we should mention. It involves the "randomness" of preventive patrol. With nonoverlapping sectors, preventive patrol coverage in a sector is reduced to zero whenever the corresponding patrol unit is busy. Anyone, including potential criminals, can monitor a patrol unit's activity in some manner (e.g., visual observation, listening to the police radio) and determine when a particular car is not patrolling. Then, since units are assigned to nonoverlapping sectors, a crime can be committed with assurance that the patrol unit will not pass during the commission of the crime.

Given the undesirable features of a nonoverlapping sector system, how can an administrator revise and improve operations? First, if the sector concept is to be retained, the large fraction of calls which are low-priority¹⁵ (i.e., they do not require rapid response) can be "stacked" and handled by the car assigned to the sector of the call when that car becomes available. This procedure reduces the amount of flying and enhances "sector identity."

Second, the sector concept can be modified so that patrol units are assigned to overlapping areas (or sectors). This procedure enlarges the area with which each patrol officer should develop an "identity." In addition, it increases the "randomness" of patrol, a desirable outcome which is not achieved simply by stacking on nonoverlapping sectors.

Response Districts for Fire Units

A fire unit's primary response district consists of all points to which it would be dispatched if an alarm were generated there, even if all units were available. In the event of unavailabilities, the unit may also respond to alarms elsewhere. Fire departments have traditionally designed districts so that the dispatched units are the ones closest to the fire. This means that all points on the dividing line between two districts are equally close to some pair of companies.

With the modification of interpreting "closest" in the sense of "shortest travel time," one might expect this procedure to minimize overall response time. However intuitively reasonable this rule-of-thumb may appear, a recent analytical study by Carter, Chaiken, and Ignall [13] has shown that "equal travel time" dividing lines are usually not optimal and that overall average travel time is minimized by following a policy that often requires a unit other than the closest unit to be assigned to a particular fire.

The philosophy underlying this result is one that often appears in systems with unpredictable demands in the near future - it may be preferable to incur an immediate travel-time penalty so that the system (e.g., the collection of all fire apparatus) is left in a state which best anticipates future demands. That is, assigning, say, the second closest unit to the most recent fire may result in favorable positioning of units for the next reported fire, thus minimizing expected overall response time. Assignment of the closest unit to the first fire might have required an unusually large amount of time to respond to the next reported fire.

Carter, Chaiken and Ignall have also shown that the boundaries which minimize overall average response times will, in many cases, also reduce workload imbalance (where workload imbalance is defined to be the difference in

the fraction of time worked by the busiest unit and by the least busy unit). Thus, implementation of their derived procedures can result in reduction in both response time and workload imbalance.

Their boundary structuring procedures have been worked out in detail for the case of two cooperating units; current research is being directed at extending the results to systems with many cooperating units. The qualitative features of the results have already been used to arrive at preferable dividing lines in New York City Fire Department operations - and these results are currently being implemented.

IV. LOCATING UNITS AND FACILITIES

Closely related to problems of response area design are problems of location, including

- o which site to select for an additional facility;
- o when consolidating two or more existing facilities into one new facility, where to place the new facility;
- o pre-positioning, or where to locate units at the start of a tour;¹⁶
- o repositioning, or how, and under what circumstances, to change the locations of units during a tour to correct for unavailabilities as they develop.

Although there is an extensive literature on the subject of "facility location," most of it is presented in economic terms and ignores probabilistic aspects of operations. ReVelle, Marks and Liebman [54] recently reviewed a variety of applications of algorithmic location theory to public sector problems without discussing the allocation of urban emergency units. To the extent that analytical methods have been used for locating emergency service units, the

application has been limited to a small number of units or to a small number of potential sites for the units. Under these circumstances, one can either determine the travel-time properties of all possible combinations of locations or utilize simple algorithms which assist in searching for the optimal locations.

In the work of Savas [56], the implications of dispatching ambulances from two fixed locations in a particular part of Brooklyn (as an alternative to the previous single site) were explored by considering every possible division of n units between the two locations and using a simulation model to estimate average response times. Larson and Stevenson [48] also considered only two sites, but the location of one of them was permitted to be arbitrary. A steepest-descent search routine enabled them to find the location of the second site which minimized average travel time. The results suggest that the optimal location of a new site is rather insensitive to the precise locations of existing units. Hogg [31] considered nineteen potential sites for fire units in Bristol, of which at most 9 were to be occupied. For this purpose, she developed an algorithm for rejecting the least desirable sites.

A considerably larger body of analytical work has been completed, or is underway, concerning the repositioning of units during the course of a tour. Two examples are discussed below.

Local Repositioning: Police Patrol Cars

Consider the case of two square patrol sectors which have a north-south boundary in common. We will assume that each unit patrols its sector randomly, and the demands are uniformly distributed over the entire two-sector region. Each unit responds in its own sector, unless it is unavailable, in which case the other one responds.¹⁷ The question of interest is, "At the moment when one of the units become busy, is there any advantage to repositioning the remaining available unit? If so, how should this be accomplished?"

Whenever one unit becomes unavailable, consider the following three alternatives for the free unit:

Alternative 1: The free unit continues to patrol its original sector (i.e., no repositioning).

Alternative 2: The free unit patrols both sectors uniformly (i.e., "uniform repositioning").

Alternative 3: The free unit is stationed on the boundary line between the two sectors at the north-south halfway point (i.e., "fixed point repositioning").

It is straightforward to show [44, p. 351] that Alternatives 1 and 2 have the same average travel distance¹⁸ and the distance for Alternative 3 is 75 per cent as large. Thus, in an average travel distance sense, uniform patrol repositioning (Alternative 2) offers no advantage over no repositioning (Alternative 1). On the other hand, fixed point repositioning offers a 25 per cent reduction in average travel distance when compared to Alternatives 1 and 2. Similar results hold [44, p. 353] for regions of four cooperating sectors and for more complicated examples.

The results suggest that any local repositioning (among nearby sectors) is advantageous in a travel distance sense only if patrol is concentrated near the boundaries of the appropriate sectors. In practice, strict fixed point repositioning may not be advisable because of lost preventive patrol coverage; still, if the free unit must remain patrolling, a large part of the travel distance reduction can be retained provided the patrol occurs near the appropriate sector boundaries. In fact, we have heard patrolmen remark that on an informal basis two units will occasionally agree to "cover" both sectors when the other unit is unavailable; this "covering" usually takes the form of concentrated patrol near the common sector boundary. To gain travel distance

reductions when such covering occurs, it is necessary that the dispatcher be aware of the identity of the cooperating units so that he can assign the covering unit to a call in the busy unit's sector.

Global Repositioning: Relocation of Fire Units

By "global repositioning," we mean the reassignment of one or more available units to areas which may be at some distance from the areas to which they are currently assigned. For many years urban fire departments have relocated available units when a number of units in one area become busy fighting a large fire. Indeed, these relocations are pre-planned, so that when a second alarm (or higher) is sounded, specified units respond to the fire while other units simultaneously move into certain fire houses which have been vacated by units at the fire. Such large-scale repositioning is not as widely used in other urban service systems, although situations continually arise (e.g., police precinct-level congestion) in which repositioning of forces would reduce travel times and dispatch delays or provide some preventive patrol.¹⁹

The following factors are important in determining whether to make a relocation:

- o How long is the expected duration of the existing unavailability?
- o How many units will have to relocate to accomplish the desired final locations?
- o How long will it take for the units to travel to their new locations?
- o Is the magnitude of the expected improvement in performance large enough to warrant the effort required to move units?
- o Is there a good reason to believe that the units to be moved

will be needed at their present locations in the near future?

Work still in progress at the New York City-Rand Institute is designed to produce an algorithm which will operate in a computer-assisted dispatch system and will recommend relocations both for large fires and for unavailabilities which occur through an accumulation of smaller fires.

Several approaches have been tried. Swersey [61] developed an integer programming model to determine which fire houses should be empty and which full. His objective was basically to minimize the average travel time to incidents, taking into account the average time that busy units would remain busy. In addition his procedure provided a penalty for each unit relocated. Once a solution to this model has been found, a standard assignment problem can be solved to recommend which units should move to which empty houses. Unfortunately, it was not possible to solve Swersey's model rapidly enough, using either branch-and-bound or approximate heuristic techniques [63], to make it an appropriate tool for real-time applications.²⁰

The relocation method which is now planned for implementation has been developed by Kolesar and Walker [40] based on a suggestion of Chaiken. Instead of focusing on average travel time, which can be close to minimum for a variety of states of the system, this method utilizes ideas of "coverage." A point is said to be "covered" if at least one available engine company (or ladder company) is within T minutes of the location. If one or more neighborhoods are expected to be uncovered for an undesirable amount of time, a heuristic algorithm first determines which vacant houses to fill, then which available units to relocate to the vacant houses. While this algorithm is not "optimal" in any sense, it appears to compute very reasonable relocations using a comparatively small amount of computer time.

V. CRIME PREVENTIVE PATROL

Although other urban service agencies have certain patrolling activities (e.g., fire departments "patrol" areas looking for fire hazards), the patrolling function is most important in urban police operations. A patrol unit is said to be performing "crime preventive patrol" when passing through an assigned area, with the officers checking for crime hazards (e.g., open doors and windows) and attempting to intercept any crimes in progress. By removing opportunities for crime, preventive patrol activity is supposed to prevent crime. By posing the threat of apprehension, preventive patrol is supposed to deter individuals from committing crimes.

Most mathematical studies of police preventive patrol have occurred in the past several years, although some earlier work in "search theory" is also relevant to the problem. The term "random patrol" was introduced into police literature in 1960 by Smith [58] who stressed the need for unpredictable patrol patterns. Blumstein and Larson [4] developed a simple analytical model for spatially homogeneous random patrol in order to estimate the probability that police would pass a crime in progress. Elliott [25] quoted one of Koopman's [42] search theory results and attempted also to compute probabilities of space-time coincidence of crime and patrol. Bottoms, Nilsson and Olson [6] have applied some of these ideas to operational problems in the Chicago Police Department.

To illustrate one simple model, consider the problem of estimating the probability that a patrolling unit will intercept a crime while in progress. For a crime of short duration T_c which occurs on street segment i one can

argue that a reasonable upper bound estimate of the probability of space-time coincidence of crime and patrol is

$$P_c = s e_i P_p T_c / L,$$

where

s = speed of patrolling vehicle

e_i = a number between 0 and 1 reflecting the relative patrol coverage of segment i

P_p = fraction of total time spent patrolling²¹

L = a weighted sum of the segment lengths in the patrol sector, the weights being the e_i 's.

Even this simple formula provides certain insights. It illustrates that crime-intercept probability is directly proportional to coverage (e_i), fraction of time spent patrolling (P_p), duration of the crime (T_c), and patrol speed (s)²² and is inversely proportional to a weighted sum of segment lengths (L). The interaction of the response and patrol activities is also apparent: during periods of heavy call-for-service demand (i.e., when P_p is small), crime intercept probability is small. A potential trade-off exists between the amount of screening and/or delaying of calls for service, reflected in the value of P_p , and the likelihood of intercepting a crime in progress.

In applications of this formula one typically finds intercept probabilities below 1 in 100. Such low detection probabilities bring to question whether the threat of apprehension provided by preventive patrol is actually great enough to deter crime.

Given such scarcity of preventive patrol effort, any effective allocation of effort must reflect the relative likelihoods of crimes occurring at various times and places. Even raising intercept probabilities from 0.01 to 0.02, say, could result in a doubling of on-scene apprehensions. By structuring a

model of preventive patrol operation one finds that the allocation of preventive patrol effort is mathematically similar to an allocation of search effort problem studied by Koopman [42] and reformulated by Charnes and Cooper [17].

Application of search theory ideas to allocating relative patrol effort (e_i 's) to maximize detection probabilities yields the following properties:

- o On street segments with sufficiently low crime rates, no preventive patrol effort should be allocated.
- o On segments which should receive preventive patrol effort, the effort should grow slower than linearly with crime rate.

This behavior again illustrates the inadequacy of linear hazard formulas which imply that preventive patrol coverage should be directly proportional to frequency of crime occurrence. Although much more refinement of these techniques is required before they can be implemented by police, we would expect the qualitative feature of the solution to hold.

VI. SIMULATION MODELS FOR EVALUATING PROPOSED CHANGES IN ALLOCATION PROCEDURES

An agency administrator is typically faced with a number of proposed changes in his allocation policy at one time. For example, the results of the models described in previous sections may suggest that he should adopt priority queuing schemes, add units at certain times of day, select new locations for some units, change response areas or patrol patterns, and modify the procedures for relocating units. In addition, certain technological innovations such as automatic car locator systems may have been proposed to accomplish some of the same objectives. Before making a choice among the alternatives, the administrator will want to have a realistic comparison of the benefits which can be expected from each approach.

For a thorough evaluation of such a comprehensive change in allocation procedures, one generally has to turn to much more complex and detailed models than the ones already discussed, for example simulation models. These models can provide information about the effect of a proposed policy change on a wide range of variables: response times to particular types of calls, workload of units, queuing delays, availability of units, etc. Such simulation studies have been undertaken by Savas [56] to investigate the reduction of travel times which could be achieved by spatially repositioning ambulances, by Swersey [60] to analyze the operations of the dispatch centers of the New York City Fire Department, by Carter and Ignall [11] to compare a wide range of combinations of fire department allocation policies, by Larson [44] in a study of the allocation of police patrol and the potential benefits of utilizing a car locator system, and by Adams and Barnard [1] to study the value of an automated dispatch system for the San Jose Police Department. Recent work on efficient computer coding of geographical data [7,35] has been of some assistance in designing such simulation models of urban emergency service systems.

A common feature of these studies has been the finding that rather simple and inexpensive administrative innovations can often make a contribution to system performance which is equivalent to that of much more expensive hardware or increases in manpower. Swersey's study [60] provides such an example. In this case, the fire dispatching office in Brooklyn was experiencing an increase in alarm rates and consequent delays prior to dispatch of units which were beginning to be of some concern to the Department. The simulation showed that computerized methods for recording, storing, or retrieving location information about alarms would not solve the essential difficulty, which had to do with the fact that a single man had final responsibility for every dispatch decision.

Swersey's suggestions for dividing this responsibility, a basically administrative change which has been implemented, provided substantially decreased delays during peak-alarm hours.

Similarly, Larson's simulation [44] has demonstrated that the absence of an explicit priority structure for calls to police departments produces unnecessary delays for urgent and moderately important calls. Most departments have been reluctant to implement such a structure, stating that their policy is to provide rapid service to all citizens. However, some departments [21,22] have begun to reject some calls and implement priority structures for dispatching cars to the remainder.

In addition, the Larson simulation was used to study the best use of automatic vehicle locator systems in police departments. The technology of such systems is well developed [39,55], and recently field tests and operational installations have been reported [9,19,23,30,32,68]. Each system provides a central dispatcher with estimates of the positions of all service units (e.g., buses, patrol cars, taxicabs) and with other status information (e.g., current speed and direction, current type of activity).

In the Larson study [44, p. 289] analysis showed that superimposing an automatic vehicle locator system on a patrol force assigned to nonoverlapping sectors causes an average travel time reduction in the order of 10 to 20 per cent, the exact value depending on the fraction of time each car is busy, number of sectors in a command, spatial distribution of calls, etc. Analysis also showed that a system with fully overlapping sectors utilizing car position information has approximately the same travel time characteristics as current nonoverlapping sector systems without car position information. Thus, if there are reasons to want overlapping sectors, even to the extent of not assigning sectors to cars, there would be little or no degradation in travel

time characteristics of the overlapping sector system, compared to current systems, provided high resolution car position information is available. Apparently, the prepositioning advantages gained by assigning cars to mutually exclusive sectors are recovered by knowing exact car positions in a system with no deliberate spatial prepositioning.²³ (As mentioned in Section II, arguments based on "regional identity" and "randomness of patrol" seem to favor some type of overlapping sector plan.)

This analysis is an example of an instance in which applying technology to a system "operating as usual" may not fully utilize the new technological capabilities.

SUMMARY AND CONCLUSIONS

Many of the allocation problems experienced by emergency service agencies, whether police departments, fire departments, or ambulance services, are not unique to any particular agency, nor are they confined only to the largest cities. Typically, an increasing rate of calls for service over a period of years creates a situation in which a substantial fraction of callers with urgent emergencies must wait "too long" for the arrival of a unit. Moreover, the agency's field personnel may be spending so much of their time responding to calls that they are unable to pay adequate attention to other important duties, or they may feel overworked.

Hiring a large number of additional personnel and providing them with new units, stations, and other equipment can almost always resolve the problem, but this solution may be neither feasible nor necessary. To determine the best course of action, an agency administrator should consider a variety of alternatives, using quantitative methods to estimate the potential benefits of any combination of them.

As a first step, the arrival patterns of calls by time and place should be analyzed, with attention paid to the number of calls which do not require immediate service. This may lead to plans for queuing or rejecting the calls of lowest priority, in which case callers should be informed as to whether a unit will be dispatched. Next, the number of units actually needed to serve the remaining calls and perform other essential functions should be determined in accordance with the methods of Section II. This analysis may reveal opportunities for improving service by moving units from one region to other or changing the hours of day at which units operate. On the other hand, the results may show that the desired level of performance cannot be

achieved without adding units, in which case the administrator will have a good estimate of the actual number of men needed.

Next, the locations (or patrol areas) and the dispatching rules for the units should be scrutinized to isolate opportunities to reduce delays further and balance workloads, using the methods described in Sections III and IV. In addition, plans should be made to reposition units as the need becomes apparent, since no static plan for locating the units can produce the best allocations under all circumstances. Police departments should also consider the extent to which preventive patrol can be enhanced by designing overlapping sectors and by providing the patrolmen with guidelines for their patrol patterns.

Although in many instances we do not yet know how to make the link between true measures of performance of emergency systems and the quantities which can be studied using analytical models, it is now apparent that models can indicate clearly which aspects of performance are likely to improve or to be degraded as a result of a specific policy change. Many of the research goals for allocation of police patrol forces proposed in 1968 in a study for the Department of Justice [5, p. 168] are now being approached, if not achieved. Wide interest is now apparent, as illustrated by reported applications of quantitative techniques in police departments in Boston [43], New York [65], St. Louis [50], Chicago [18], Cleveland [28], Tucson, Arizona [3], Phoenix, Arizona [14], and Great Britain [8]. The whole subject of the allocation of fire units has been developed in the past two or three years and has given an entirely new complexion to fire research. In the next few years we expect that the models will improve in their sophistication and utility and agency administrators will make increasing use of quantitative models as their virtues become apparent.

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FOOTNOTES

1. Typically, a little more than 5 man-years are required annually to fill a single post around the clock. Thus, the direct manpower costs of operating a two-man patrol car in New York are approximately \$120,000 per year, and a single fire engine may cost over \$500,000 per year.
2. Congested radio frequencies often prohibit this type of location procedure.
3. This pattern is also common for emergency repair services, in which the driver may contact the dispatcher at the end of one service to determine where he should go next.
4. Under some circumstances, the probability that an alarm is false is known to be high, and the response can be adjusted accordingly.
5. Some requests for service are generated by field personnel, as when a fire chief signals a second alarm at a fire, or a patrolman calls for assistance over his radio. Such calls can be immediately identified as reliable and of high priority.
6. The results of this queuing calculation are not the sole basis on which cars are assigned to districts, since St. Louis also has a "preventive patrol" force which does not respond to calls, unless they have a very high priority. However, the use of queuing theory is an essential component of the allocation policy of the St. Louis Police Department.
7. The dependence of service times on the number of busy units is characteristic of most urban emergency systems, but it is difficult to measure quantitatively. One cause of the variation, which can be estimated at least roughly (see below), is the increase in average travel time which occurs

when distant units must be dispatched to calls. More important, however, is the fact that an incident may escalate when units do not arrive promptly; a small fire may become much larger and require a longer time to extinguish, or a reported marital dispute may result in serious assault before a patrol car arrives. Available data are rarely adequate to model these phenomena [34].

8. Some units may leave the fire scene when the fire is under control, while others will remain until extinguishment, and still others will continue to work after extinguishment on some duties known as "overhaul."
9. See Section II. A.
10. See Section II. A.
11. The assumption that travel time is a constant multiple of travel distance may be a suitable approximation in some cases, but it should be checked against the data.
12. For a general discussion of criteria which are appropriate for police patrol, see the report of Kakalik and Wildhorn [36].
13. More precisely: among all quadrilaterals of a given area, the one with the smallest maximum distance between two points is a square.
14. Several interesting applications of this "right-angle distance metric" and other metrics have been discussed in References 26 and 57.
15. For instance, even for those calls which are related to crimes, typically 75 per cent are "nonemergency" and thus do not require rapid response. [62, p. 91].

16. "Tour" refers to the period of time during which a specific group of men will be working.
17. In this simple example we assume that calls arriving when both units are busy are handled by units outside the two-sector region.
18. Similar results hold if response time rather than response distance is used.
19. The absence of global repositioning as a standard technique in police patrol operation may be explained by the fact that an accumulation of small incidents, rather than a single large incident, is most often the cause of whatever unavailabilities exist. Even fire departments are not likely to provide relocation guidelines for dispatchers to use in cases when several small fires produce as many vacant fire houses as a large fire might.
20. The model can, however, be used to solve the simpler problem of determining where to reposition n units (fewer than the number of houses) in order to minimize expected response time when all n units are available.
21. The remainder of the time is spent answering calls and performing other duties.
22. If it were possible to make s fairly large, the ability of the patrolmen to identify suspicious events when passing at high speed would have to be included in the model. But usually s is in the range 5-15 mph and cannot be adjusted at will.
23. These statements are subject to the assumptions of the models used, the most critical of which is the assumption that the cars patrol independently of each other.

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