CHAPTER 7: PATIENT TRANSPORT

THE SITING OF AMBULANCES IN URBAN AREAS

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Can a computer save lives? It can if it aids in the deployment of ambulances, allocating these limited resource emergency services in a more efficient pattern relative to points of need.

Two decades of remarkable growth in our ability to site emergency services is being capped by our ability to model the random events of call arrival within the theory of optimal siting, thereby enabling the siting of ambulances with specific reliability levels specified for the service response.

This paper traces the development of the ambulance siting models from their relatively simple beginnings to the present. All of the models fall under the rubric of covering problems. "Covering" is a term drawn from the literature of Operations Research that describes optimization models which seek to provide "coverage" in nearness or relationship to all of the elements or members of a group. Coverage of a demand area by an ambulance means that the ambulance can reach the demand area from its current position within a stated time standard.

In looking back at the evolution of the emergency service siting models, we can see that their development has proceeded in a relatively predictable and rational fashion. The first models were relatively simple to state and to optimize, but they assumed away some important aspects of practical siting problems. As the implications of the models sank in, however, researchers saw that additional practical features could be included and the resulting models could still be solved. More ways were then found to state and solve these problems, and the problems grew in realism. Many of these developments are traced in a recent review (ReVelle, 1988) which provides greater detail as well as the mathematical underpinnings of the siting models discussed here.

PRIMARY COVERING MODELS

The first of the emergency services covering models was the location set covering problem (Toregas, et al. 1971). As in all of the covering models which follow, the initial assumption is that siting takes place at positions on a road network and that areas of demand (abstracted as nodes) require coverage. Eligible responder positions are indicated as being available on the network at which responders can be sited and from which responders can respond to calls from the demand areas. The distances or times that separate the responder sites and areas of demand are given in advance or can be calculated. The location set covering problem seeks to answer the following problem: Find the smallest number and the positions of the ambulances such that all demands have at least one ambulance stationed to respond within a time or distance standard.

This is a systems analyst or applied mathematician's problem statement, articulated in a paper in 1971. Only a year before, Huntley (1970), a physician, had independently asked virtually the same question: "How many ambulances? Are there enough? What is an acceptable response time? Usually in a metropolitan area, it is 15 minutes... If a 15 minute response time is demanded, how many ambulances are required? Where must they be positioned to provide reasonable assurance that this criterion is met?"

The location set covering problem can be structured as a 0,1 integer linear program. Surprisingly, the linear programming (LP) relaxation of the 0,1 program provides the optimal (0,1) solution in most practical problems (about 95% of the time). A simple cut constraint can be added to resolve nearly every problem which relaxed linear programming fails to resolve in integers. Problems on the order of a thousand demand and supply areas have been solved in this way, and problems with ten thousand such areas would seem capable of solution on mainframe computers using modern LP codes. Other efficient computational procedures for the problem are available, including a method that relies solely on logical "and" and logical "or" operations.

The simple location set covering problem utilizes a time or distance standard for travel that takes place from responder to demand area. The final destination of the ambulance, however, is usually not the area of demand, but a hospital. A time standard can be applied to this two-service link problem. The modified problem is to site the least number of ambulances in such a way that the calls arising at all demand areas can be reached by a responder and transported to a hospital within a specified travel time standard. When hospitals are located centrally, ambulance dispatching stations move to the periphery of a region to bring all demand areas within the two-link time standard.

The location set covering problem quickly found exploratory application in major American cities. Public Technology Inc., a division of the International City Managers Association, marketed the tool, using the formulation and solution method in conjunction with shortest path matrices. The approach of Public Technology, Inc. was not one of actual optimization but was intended to heighten awareness of locational alternatives to achieve coverage standards. In fact, such use is probably one of the best ways to apply the models which follow - as a means to generate alternatives for decision makers to weigh and consider.

Within a few short years, however, researchers recognized several serous inadequacies of this basic model. First, the quantitative extent of demands, that is the frequency of calls, was ignored in this basic mode. Each demand node was allowed to require coverage within the time or distance standard independent of its need as measured by call frequency. Second, the cost to cover the more distant demand areas had not been considered. From practical experience with the location set covering problem, it appeared that the requirement for coverage of every demand node, independent of need or position, could push the requirement for ambulances to levels which could not be afforded.

These two considerations, the frequency of demand and the cost implication of the number of ambulances required, led to a new formulation and a new interpretation of the location question. Based on these considerations, the maximal covering location problem (Church and ReVelle, White and Case) sought to answer the following question:

Given a limited number of ambulances, at what sites should the ambulances be placed so that the maximum number of people (or calls for service) have an ambulance stationed within the travel time standard?

Again, a 0,1 integer program can be structured to answer this question. The integer program can be solved exactly by solving the linear programming relaxation and applying, as required on occasion, several stages of branch and bound. Alternatively, several efficient heuristics (see Church and ReVelle) have been provided which quickly locate excellent solutions with values of coverage within one or two percent of the best value of coverage. Problems with a thousand nodes can be solved on modern computers using linear programming codes, and problems with ten thousand nodes should be solvable on supercomputers.

In this version of the location problem, the number of responders is given or can be specified at each of a number of different levels in order to investigate the impact of the number of responders on the population that can be covered. This tradeoff between the number of optimally sited ambulances and the population covered within the standard seems to indicate that coverage of the last 10-20% of calls is quite expensive, that is, coverage of the last 10-20% of calls requires a very large additional increment of ambulances. An application of the maximal covering location problem to ambulance deployment in Austin, Texas won a prize from the Operations Research Society and the Institute of Management Sciences in 1984 (Eaton, 1985).

ADDITIONAL COVERAGE MODELS

Although excitement in the research community accompanied the development of these early models, a nagging question accompanied their creation and implementation. That nagging question was: "What does coverage mean if, when a call arrives from a particular demand area, the responder or responders which may be the sole coverer(s) of the demand area are busy with another call? Is that coverage?" It gradually became clear that these first modern EMS siting models carried the burden of an implicit assumption: namely, that the primary responder, the responder stationed within the time or distance standard, would be very likely to be available at the time of call arrival. That assumption in turn implied that the relation of the rate of call arrival relative to the rate at which service could be provided was such that a sole coverer within the standard would nearly always be available when a call arrived from the demand area in question. Under such a circumstance, with the system uncongested, the covering models mean what they say and accomplish what they are meant to accomplish.

If the system is congested, however, with a high rate of calls relative to service capability, the covering models guarantee no more than the initial placement of a responder within the coverage standard. Actual availability is not ensured. The recognition that a sole coverer may not actually be available led to a new generation of deterministic siting models, those that emphasized additional coverage within the time standard, additional coverage beyond the first for the demands areas of the system.

The first models of those that focused on additional coverage were oriented toward the deployment of ambulances; that is, they considered only a single type of responder. Also, the additional coverage models all began with the assumption of a limited number of ambulances available to be placed on the network. There is a simple solution to additional coverage, but it is expensive. In seeking additional coverage, it would be possible to require simply a second coverer for each demand point in the format of the location set covering problem. That is, we could seek the minimum number of responders, so that all demand nodes have at least two responders sited within the time or distance standard. That would be a very costly solution, however, as the required number of responders would be likely to double or nearly so. As a consequence, we are left to seek other ways to achieve additional coverage, ways that do not require it, but seek it to the maximal extent possible in the context of limited resources.

The first such additional coverage model sought to deploy a limited number of ambulances and required that all demands be covered at least once within the distance or time standard. Obviously, the number of ambulances being deployed was greater than or equal to the least number required to cover all demands at least once. In that sense, the solution was already costly, but the concepts developed rather than the specific model utilized are the important contribution here.

The concept can best be seen by considering a single demand area. It would be best if each demand area enjoyed - in addition to its required responder within the time standard - as many additional coverers within the standard as could be placed without sacrificing the required coverage of any other demand area. In that way, if the closest responder is busy when a call arises at the demand area, the likelihood of a second responder being available (free to respond) within the time standard is enhanced. The notion of a deployment pattern which emphasizes additional coverers within the standard is then extended to all demand areas. Finally, one seeks to deploy the limited number of ambulances in a way that maximizes, over all demand areas, the total of additional coverers, while requiring at least singe coverage for all areas. (Daskin and Stern, 1981, Berlin, 1972). The problem may be formally stated as:

Given a limited number of ambulances, find the positions for these vehicles which maintains the requirement of primary coverage of all demands within the standard and distributes the ambulances in a way that maximizes the sum of additional coverers in the system. An additional coverer is a coverer within the standard in addition to the primary coverer.

Researchers soon noted that such a deployment sought additional coverers without regard for the actual frequency of calls for service at any particular demand area. An intelligent modification (Eaton, et al., 1986, Benedict, 1983) suggested that the additional coverers for a particular demand area be weighted in the objective by the call frequency or population of the demand area. The consequence, of course, is that the higher the call frequency or population of an area, the more likely it will be to have additional coverers. All of these models can be readily solved for very large numbers of nodes (thousands) by relaxed linear programming and, on occasion, a small increment of branch and bound.

Another more targeted approach to additional coverage is to seek to achieve only a minimum specified number of additional coverers for each demand area, perhaps one backup responder (Hogan and ReVelle, 1985). Then one seeks to maximize the people or calls which have two or more responders (one backup plus one primary responder) within the time standard given that each demand area is covered at least once. The concept of weighing the backup coverage presence by population or call frequency is retained as in the preceding model. Additional coverers, beyond the backup responder, however, are not valued in the objective. Such additional coverage occur but is not explicitly sought or counted. Again, this model has the shortcoming that first coverage is always required - a costly alternative.

The problem may be stated as: given a limited number of ambulances and the requirement that all demand areas are covered by at least one ambulance sited within the time standard, deploy the ambulances to positions that maximize the number of people or calls that have at least one backup responder also sited within the standard, thus to enhance the likelihood of a responder being available to respond from within the standard.

To alleviate the burden of required first coverage, Hogan and ReVelle (1985) structured a formulation which utilized two objectives: maximum first coverage weighted by population or call frequency, and maximum backup coverage (presence of a second responder) weighted by population or call frequency. Only a limited number of ambulances were available for deployment, and coverage beyond the second was not valued or counted. A tradeoff curve was developed to show the impact on first coverage of emphasizing second coverage.

Obviously, the more importance attached to maximizing first coverage the lower second coverage will be, and vice versa. Surprisingly, however, substantive increments of backup coverage were found to be obtainable without significant sacrifice of the population enjoying first coverage. Both of the backup models of Hogan and ReVelle are solvable by linear programming relaxation and such occasional branch and bound as may be needed. Very large (thousands of nodes) problems are capable of solution even without the supercomputer.

The last model in this group also relinquishes the requirement for first coverage. Storbeck and Vorha (1988) seek to maximize a weighted sum of the population receiving first coverage and the population receiving additional coverage. Storbeck and Vorha place explicit continuing value on additional coverage beyond the first backup coverer.

All of these additional coverage models introduce the same new feature to siting models. The new feature is that each facility site can now house and deploy more than a single responder. This property occurs because additional responders beyond the first for a demand area are now explicitly valued. One, two, three, or more responders can be placed at a facility site in any of these additional coverage models. In contrast, in the primary covering models, there was never any reason to site more than a single responder at any position.

PROBABILISTIC (RELIABILITY) MODELS

The models of the preceding section - those that deal with the placement of additional responders within the standard - are all attempting to come to grips with what is essentially a random phenomenon, the actual availability of a responder to an individual demand area within the time or distance standard. In the past six years, the emergency services siting models have finally found the tools and methods to focus in a coherent and creative way on the issue of randomness in responder availability. The process is under way, but many challenges and much research remain as we come to grips with randomness in responder availability.

The first steps in the process of dealing with randomness began naturally enough with the simple models, those which considered only a single type of emergency responder. An early approach, lost to researchers for almost ten years, was a probabilistic version of the location set covering problem (Chapman and White, 1974). To make that model work, the authors were required to assume that the busy fraction, the proportion of the time that a responder is busy, is known in advance for the responder at each site. The easiest assumption to make is that the busy fraction takes the same value for all responders no matter where they are deployed on the network. It is easy to calculate an average busy fraction in the system based on the total rate of call arrival, on the call duration and on an initial estimate of the number of responders. This busy fraction is then applied to all responders independent of their positioning. By utilizing this value, we can write a reliability constraint for each demand node.

Each such reliability constraint specifies the minimum proportion of occurrences in which a responder must be available to the demand node within the time standard. For instance, the reliability constraint might say that a particular demand node must have a responder available to respond from within the time standard in 90 out of 100 of the calls originating at that demand node. This reliability constraint may be enforced at different levels of required probability for each demand node if it is desirable. Such a differential constraint might be written for a school or a stadium or a nursing home. Most versions of this problem have so far specified the same level of reliability be availability for each node.

That earliest probabilistic siting model sought the minimum number of responders (ambulances) so that each demand area had a responder available within the time standard with the required level of reliability The model suffered from a severe inadequacy: no method other than a very rough averaging method was available to estimate reasonably the busy fraction of each ambulance. Although this particular siting model disappeared from view for ten years, its assumptions were rescued and used creatively by Daskin, 1983, who also recognized that responders were not always available. The objective of Daskin's siting model was to maximize the expected population covered, given a limited number of deployed ambulances. The objective was built up from the sum of the products of the population and the expectation of responders available to that population. Daskin's model sparked the present line of research on probabilistic siting models, models which provide more accurate estimates of busy fractions, beginning with ReVelle and Hogan models.

Focusing on ambulance deployment, ReVelle and Hogan, 1988, realized that the assumption of a uniform system-wide busy fraction was unrealistic. From studies of the Baltimore ambulance system, they were aware that the ambulance crews at the various sites faced workloads that varied from four to almost 20 calls per day, despite the best creative efforts by an experienced chief of ambulance operations to redeploy the crews to even out workload. A team of analysts tried as well to even out the workload, but were also unsuccessful. ReVelle and Hogan, thus developed a new probabilistic siting model.

As before, the objective was the minimum number of ambulances. Again, constraints assured that a responder would be available within the time standard with a prescribed level of reliability for each demand node. However, the value of the busy fraction assumed for each responder was now different. Instead of a uniform system-wide busy fraction, each area in which a reliability constraint was written had a variable busy fraction determined by both the call frequency within the area encompassed by the constraint and the number of responders within that area. These sector-specific busy fractions are the key to our rapid progress in emergency service siting research.

For additional insights, though, we still examine solutions which assume a uniform system busy fraction. The probabilistic location set covering problem may be stated as:

> Find the positions for and the least number of ambulances such that each area of demand will have a responder available to respond within the time standard with a stated reliability. The local busy fractions of the ambulances are not assumed in advance but calculated from the problem solution.

This problem statement matches in intent the Federal guidelines given by the Emergency Medical Services Act of 1973. The act called for an "adequate number" of emergency vehicles, a number that was interpreted as a value sufficient that 95% of requests for assistance be met within 10 minutes in urban areas and 30 minutes in rural areas. Once again, the model concepts match the practical statements of operational goals offered by policy makers.

Problems with several hundred demand nodes have been solved on a dedicated microcomputer, and problems with a thousand demand areas should be capable of solution on a mainframe computer. In addition to employing linear programming as a solution technique, specialized algorithms are likely to be created and utilized as well.

Both the probabilistic siting models with sector-specific estimates of busy fractions and those that assume a uniform system-wide busy fraction utilize reliability constraints. For either model these reliability constraints are converted into constraints that may require more than just one responder initially stationed within the time or distance standard. Such constraints may now require one, two, three, or more responders initially stationed within the standard. A requirement for two or more responders makes it necessary to allow several responders to be positioned at the same site; this is the same allowance that was necessary in the models that considered additional coverage.

The sector-specific busy fractions opened the way for creation of a probabilistic version of an earlier primary coverage model, the maximal covering location problem (Church and ReVelle). The maximal covering location problem in its original form sought the deployment of a limited number of responders so that the maximum (not the entire) population had a responder initially positioned with the time standard. Given that not all points of demand could be covered with the limited number of responders, the maximal covering problem sought to deploy the responders as effectively as possible. In a similar fashion, this new problem, named the maximum availability location problem, recognizes that the ambulance resources are insufficient to have responders available with the required reliability for each and every demand area. This new problem may be stated as follows:

> The maximum availability location problem seeks to deploy a limited number of ambulances in a way that maximizes the number of people or calls that actually have a responder available to respond within the time standard with the stated reliability.

As in the previous cases, this problem may be cast as a zero-one linear program and has been solved by linear programming relaxation.

With the sector-specific estimates of busy fractions and a formulation that seeks maximum availability, we are now poised to solve and have already made progress in solving, far more difficult emergency service siting problems including problems in the arena of fire protection. Challenges remain in the structuring of emergency ambulance service siting models, challenges that will improve upon and carry us beyond the new generation of probabilistic formulations described here.

In the random environment, where it is acknowledged that responders are often busy, better approximations of local busy fractions are likely to be possible. Further, it may be possible eventually to deal with dependence in responder availability, a thorny issue because dependence is a function of siting and siting a function of dependence. Also, the environment of these models is not merely random; it is also dynamic, evolving through the day, week and season. Demand may also exhibit a trend, and new demand areas may evolve over time. None of the probabilistic siting models have yet been extended to changing and evolving environments. All of these methodological challenges remain to be faced.

Although these enhancements will improve ambulance siting models still further, the most recently developed techniques are now ready to be applied in practice and can significantly aid the decision making process in ambulance siting. These models assist the intuition of even the best chief of ambulance operations and can provide a firm foundation of support for rational decision making.

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AEROMEDICAL EVACUATION IN JAPAN

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Aeromedical evacuation may be said to have two facets, evacuation by helicopter over short distances and fixed wing aircraft over long distances, such as domestic and international transportation of sick or injured patients. This paper will introduce emergency air rescue services in Japan.

AEROMEDICAL EVACUATION BY HELICOPTER

Emergency rescue services have been mainly carried out by ambulance in Japan. In a few prefectures with many scattered islands, helicopters are now used only for special and sporadic cases.

Japan is made up of four main islands, Hokkaido, Honshu, Shikoku, and Kyushu, and more than 3,000 smaller islands. Its greatest span is 3,000 km and its total land area 377,643 km^2, 72% of which is mountainous; the remainder is flat land. The population is about 122 mn and the average population density is 329 people per km^2.

Under the national government, there are two levels of local autonomy: 47 prefectures at one level, and municipal bodies of 659 cities, 1,999 towns and 591 villages at the other level. Each body has its own autonomous government with an elected assembly.

By law, emergency medical services are administered by the Health and Environmental Protection Department of the prefectural government, and emergency rescue service by ambulance is provided by the fire department in each municipal body. There are 5,869 first aid facilities and emergency hospitals, 3,021 organized rescue systems, 4,443 ambulances and 45,805 ambulance crew members.

For an emergency rescue, a patient will usually be transferred to first aid facilities and/or the emergency department of a hospital by an ambulance, which can be called by telephone. It is very rare for a doctor to come to the scene of an accident or to attend a critically ill patient in the ambulance.

In general, the ambulance crew rushes to the scene of the accident or the house of a seriously ill or injured person and carries him to the hospital; hardly any attempts are made to save the patient's life on the way to the hospital except for the administering of first aid.

The ambulance service network has been operational since 1963. In 1987, 2,426,852 patients were transferred by ambulance; 56.5% were transferred within 20 minutes of the telephone call. Of these, 69.8% were transferred to private hospitals and the rest to public hospitals (municipal, prefectural or national) which were rarely prepared or staffed to provide prompt, complete, or advanced medical care for all emergencies. A few hospitals have a landing field for rescue helicopters; there are few aeromedical evacuation systems present in Japan.

Under these circumstances, the need for evacuation by helicopter from the scene of an accident was not recognized until recently. Only special, sporadic cases have been transferred over long distances in helicopters Self-Defense Forces, the police or the fire department have been used routinely for the evacuation of seriously ill and injured persons from first aid facilities to a large, well-equipped hospital in Hokkaido, Tokyo, Nagasaki, Kagoshima, and Okinawa.

A private air transport company with a helicopter especially equipped for the transportation of seriously ill and injured patients was organized in 1984 and began services on Honshu island. It has not had much demand, however, because of the high costs involved.

As construction of the highway network nears completion, the need for faster emergency rescue services in highway traffic accidents has been recognized. Also, emergency rescue service by helicopter is considered important in many instances, such as the massive evacuation of victims after earthquakes or floods in isolated areas.

Therefore, the Japanese Council of Traffic Science and the National Land Agency are now carrying out experimental research on emergency evacuation by helicopter. We hope that as a result of these studies, an effective emergency rescue system by helicopter will be established in the near future throughout Japan.

INTERNATIONAL AEROMEDICAL REPATRIATION

Lately, worldwide overseas travel for sightseeing, business and so forth has increased year by year. In Japan, this number is expected to exceed seven million per year. The number of Japanese involved in various kinds of irregularities, disease, physical and psychic damages of many causes has risen in proportion to the increase in the number of travelers.

Under these circumstances, over 100 stretcher cases were carried from overseas locations in Japan on scheduled commercial airline flights, as we have no international aeromedical evacuation system in Japan now. This is very expensive and sometimes very dangerous, as commercial airlines are not satisfactorily equipped for the transportation of very ill patients.

For example, on 24 March 1988, a big train accident involving many Japanese students occurred in the suburbs of Shanghai, China. There were many difficulties in arranging for repatriation on commercial airlines; the use of oxygen in the airplane for artificial ventilation, the arrangement for doctors or nurses to accompany patients back to Japan, etc.

Recently, a system for assisting overseas travelers with the financial costs of repatriation was organized in Japan by a branch of a worldwide insurance companies' network.

On the other hand, within this year, the Japanese government will receive two Boeing 747-400s for various official uses. We hope these airplanes may be able to be used for rescue flights by the Japanese Medical Team for Disaster Relief (JMTDR); and for the transfer of medical equipment to overseas areas.

But unfortunately, it will be very difficult to use these airplanes for private purposes. So, we now intend to organize a non-governmental international repatriation system which will be able to move freely between Japan and overseas areas.

For this purpose, the International Affairs Committee of the Japanese Association for Acute Medicine, most of whose members are members of the JMTDR, have held discussions in preparation for organizing an emergency repatriation or international aeromedical evacuation system in Japan for sick or injured patients from and to all parts of the world.