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Source: *The Journal of the Operational Research Society*, Vol. 37, No. 2, O. R. in Developing Countries (Feb., 1986), pp. 113-126
Published by: Palgrave Macmillan Journals on behalf of the Operational Research Society
Stable URL: https://www.jstor.org/stable/2582705
Accessed: 31-01-2019 14:19 UTC

J. Opl Res. Soc. Vol. 37, No. 2, pp. 113–126, 1986
Printed in Great Britain.
0160-5682/86 \$3.00 + 0.00

Determining Ambulance Deployment in Santo Domingo, Dominican Republic

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In 1983, The Ministry of Health of the Dominican Republic (SESPAS) began planning an emergency medical service (E.M.S.) system for the capital city of Santo Domingo. This paper reports on one component of this effort, the development of options regarding the type of E.M.S. care to be delivered, by whom, via what number of types of equipment, sited at which locations. SESPAS has used the results to develop a plan for a public 'urgency care' system quite different from the uncoordinated mix of public, private and voluntary services operating previously. The system has been implemented according to plan with basic life support vehicles staffed by physicians.

Key words: developing countries, health service, location

INTRODUCTION

Santo Domingo, the metropolitan capital (Distrito Nacional) of the Dominican Republic, is approximately 1500 km^2 in size and had an estimated 1.55 million residents in 1981. It has been growing rapidly; the Office of National Statistics (ONE—Oficina Nacional de Estadística) has reported that Santo Domingo's population increased 90.6% between 1970 and 1981.[1] This growth has generated demands for expansion and improvement in metropolitan services.

Prior to 1982, no emergency medical service (E.M.S.) system operated in Santo Domingo. Each of the city's public and private hospitals possessed ambulance-type vehicles, but these were not used to respond to telephone calls for emergency medical care. The Red Cross also owns ambulance vehicles, which in principle can be used to respond to calls; in practice, they do not always respond to reported emergencies. As the Minister of Health once told the authors:

> Red Cross vehicles are not used for responding to emergency medical calls. They carry corpses . . . either corpses in fact, or in process.

Ministry of Health (SESPAS—Secretaría de Estado de Salud Pública y Asistencia Social) officials had been dissatisfied with the unreliability of Red Cross service and the low level of pre-hospital medical care, as the volunteer drivers are trained only in first-aid skills. The inadequate quality of medical care at hospital emergency rooms is an even greater source of frustration for SESPAS officials. Emergency rooms, often the route a patient takes to enter a hospital, typically are staffed by medical interns or residents, poorly equipped, overcrowded and unsanitary.

When Amiro Pérez Mera, M.D. became Health Minister in 1982, one of his priorities was to overhaul the patchwork of existing services and replace it with an emergency medical care system, including on-scene patient stabilization and sophisticated in-hospital medical care. In 1983 SESPAS obtained commercial credit from Argentina to purchase 80 ambulance vehicles, which became available for use in October 1984. In September 1983, SESPAS requested assistance through the Pan American Health Organization (PAHO) to develop plans for implementing an ambulance system in Santo Domingo.[2] This request resulted in the initiation of cooperative research between SESPAS officials and staff of The University of Texas at Austin to determine the number and location of vehicles to deploy so as to provide quality service to all segments of the population at a reasonable cost.

Cost containment, necessary given the limited budget for emergency medical care, was complicated by two pre-determined Ministry policies, physician staffing of ambulances and equal treatment of all areas in Santo Domingo. Ambulances would be staffed by physicians, so as to provide pre-hospital medical care to stabilize patients with life-threatening conditions. In the Dominican Republic, such a policy is not overly costly, as a Dominican doctor receives less pay than an American paramedic. This policy also relieves the relatively high physician unemployment in Santo Domingo. The goal of treating all parts of Santo Domingo 'equally', regardless of cost, reflected the political unacceptability of any plan that allocated ambulances so as to respond more rapidly in one area of the city than another.

DATA COLLECTION AND MODEL DEVELOPMENT

As in many other studies of emergency service deployment, the district of Santo Domingo had to be broken down into zones for analysis. In selecting a level of aggregation, the study team considered two factors. First, a sufficiently large number of analysis zones had to be used to distinguish clearly among alternative locations. On the other hand, augmenting the number of zones increases the effort required to code and analyse data as well as the computational burden involved in solving the model. Second, the zone structure had to be compatible with available sources of travel-time data and information on E.M.S. demand.

Planning was complicated by the fact that information does not exist regarding the time and location of E.M.S. calls, the cause of each incident, ambulance responses, or services rendered. Even the total number of calls reported by the voluntary ambulance services is not considered reliable.

In view of these data problems, we decided to use population as a surrogate for E.M.S. demand. As part of the 1981 ONE decennial census, Santo Domingo was divided into (a) 94 barrios, roughly equivalent to U.S. census tracts, and (b) 214 polygons, areas a bit larger than American census blocks.[1,3] We used the number of persons in each polygon as a relative weight for the likelihood of an E.M.S. call in the area.

The government of the Dominican Republic does not maintain matrices of travel times between various points in a city. Thus it was necessary to find a way to estimate the speed of ambulance travel among the polygons.

Some American cities estimate point-to-point intra-municipal travel times by developing travel forecast models. Travel time between two points is computed as a consequence of the equilibrium volume of traffic and the roadway width, as affected by various legal, engineering and behavioural variables.[3] Such transportation model development was outside the scope of this project.

Estimating travel times on the basis of observed driving times between pairs of nodes would have been beyond the time, personnel and financial capabilities of the study team. For example, over 1.8 million trips would be required for estimating travel times for arcs among 214 nodes, assuming ten observations per segment for four types of driving conditions.

Instead a 7-step procedure for estimating ambulance travel times among the 214 polygons was developed (see Table 1). A shortest-path algorithm was used to compute the expected shortest time of travel along any arc between node pairs.[4] Thus the basis for this location study was the set of

TABLE 1. *A seven-step method for estimating travel times among polygons in Santo Domingo*

1. Nodes were designated at the centre of business or residential activity in each polygon by persons familiar with the area.
2. All reasonable routes between neighbouring nodes were identified by staff of the Land Transport Division of the Dominican Public Works Department (the Dirección General de Tránsito Terrestre of the Secretaría de Estado de Obras Públicas y Comunicaciones).
3. Each block of these street segments was classified into 16 types of traffic arteries on the basis of location in the city, economic conditions, types of housing stock, nature and width of roadway, and relative volume of traffic. These road types ranged from bridges, through narrow streets in poor areas of the city centre with a high volume of traffic, to broad avenues in suburban, wealthy areas.
4. Representative long routes were selected through Santo Domingo composed of multiple examples of each type of street segment.
5. Red Cross ambulance drivers and Public Works Department staff drove these routes numerous times during four different periods of interest to SESPAS: (a) weekdays during working hours; (b) weekdays at night; (c) weekends during daylight hours; and (d) weekend nights.
6. On the basis of this multiple sampling of each type of street segment, we estimated expected mean travel speeds along each of the 16 types of streets during each of the four periods of the week.
7. These average velocities were multipled by the measured length of the streets to compute expected average travel time between adjacent nodes.

Note: Ricardo Ricardo Lantigua developed this method based upon discussions between the authors in October 1983. It required only 5 days of full-time driving to complete the process for Santo Domingo.

shortest travel times among 214 nodes, and population weights for each node, taken from the 1981 census.

We employed a number of criteria for selecting a location model for ambulance services. First, the objectives had to relate to saving lives, the goal of an emergency medical service. A system's capacity to achieve this is related to the time it takes to reach the scene of an incident and the skill levels of the responding staff. Changing vehicle locations can reduce the response time to any call, and the maximum response time has been related in the medical literature to the likelihood of patient-survival of life-threatening events.[5] SESPAS medical officials preferred the concept of 'maximum response time' as the system surrogate for E.M.S. effectiveness.

A second model requirement was compatibility with a system providing one level of care, defined in both response-time and staff-skill terms. The SESPAS decisions (a) to retrain unemployed physicians as E.M.S. staff and (b) the principle that all persons in Santo Domingo be served equally had economic implications. System costs would decrease if untrained drivers could be employed, if fewer vehicles could be deployed, or if response time could vary to different parts of the city. However, both physician-staffing and non-discriminatory service were administrative requirements defined in advance by policy makers for the study team.

A third principle was that the model should be inexpensive to use and should involve computation within the capacity of the current generation of microcomputers. Given the fact that SESPAS sought to consider many alternatives before selecting the final ambulance sites, it would be necessary to run the model many times. Although SESPAS owned a minicomputer and employed it for initial runs, the Ministry later exhausted its budget for maintaining the minicomputer. It thus became necessary to develop solution procedures which could be implemented on the personal microcomputers of the study team.

Fourth, the model had to address concerns that the system respond well during periods of relatively high volume of emergency assistance calls. Finally, the model had to be understandable to SESPAS staff and to the policy-makers responsible for implementing ambulance deployment plans.

The study team considered the full range of available emergency medical service location models: simulations,[6,7] stochastic queueing models embedded in location-seeking heuristics[8–11] and deterministic location optimization models. Both simulation and stochastic queueing models were precluded because no information existed on the temporal or geographical patterns of emergency medical calls in Santo Domingo.

There were two types of deterministic location models considered, those which do and those which do not incorporate means for providing 'back-up' coverage. Four models—set covering,[12] maximal location covering,[13] p-median[14,15] and hierarchical location covering[16,17]—were rejected because they do not deal with the 'busy ambulance' phenomenon (see Table 2). As these approaches use deterministic demand weights, the solution does not take into account the queueing aspects of calls-for-service. These models treat all calls if served by the closest vehicle, even if in reality ambulances do get busy, and service from 'back-up' vehicles would be necessary. In addition, a reason for excluding the p-median formulation is that the SESPAS staff preferred a covering objective. The various hierarchical location-covering models were not appropriate because the system involves one level of service to a single type of demand.

At the time of this study, the authors were aware of three papers that incorporate back-up coverage or in some way attempt to compensate for queueing effects (see Table 3). Daskin and Stern's hierarchical objective set-covering formulation (HOSC)[18] posits two objectives:

minimize the number of vehicles to cover all zones within time T; and
maximize the number of multiple-covered zones (those zones covered by more than one ambulance).

Their formulation deals with the issue of busy vehicles by trying to locate ambulances so that second, third or additional vehicles can respond rapidly in the event the closest ambulance is busy.

The Daskin/Stern formulation multiple-covers zones without distinguishing among them; it equally weights each zone. Although Stern indicated that demands weights could be included,[19] that problem was not formulated.

TABLE 2. *Deterministic location models which do not provide back-up coverage*

Name	Problem statement
Set covering[12]	Cover nodes with the minimum number of vehicles
Maximal location covering[13]	Maximize the number of demands covered by a fixed number of vehicles
p-Median problem[14,15]	Find locations which minimize average response time
Hierarchical service covering	
(i) Non-referral[16]	Cover different demands with distinct services from a fixed number of sites with no referral among services
(ii) Referral[17]	Same as for (i), but with either 'top-down' or 'bottom-up' referral among services

TABLE 3. *Deterministic location models which do provide back-up coverage*

Name	Problem statement
Hierarchical objective set covering[18]	Minimize vehicles and maximize the number of multiple-covered zones within a fixed upper time bound
Expected covering[20]	Maximize the expected demands that can be covered by a fixed number of facilities
Weighted benefit maximum expected covering[21]	Maximize the benefits derived from covering expected demands by a fixed number of facilities
Back-up demand coverage models[22,23]	Maximize the multiple coverage of demand within a pre-specified maximum travel time with the minimum number of vehicles

Daskin formulated an expected covering model that deals with busy vehicles by incorporating stochastic demand.[20] His formulation maximizes the expected demand that can be covered by a fixed number of facilities. The expected demand term reflects the probability that a vehicle at a facility is available for dispatch.

Daskin and Church extended expected covering to weighted benefits where a user can weigh benefits from access within one upper bound on response time as different from coverage within another time standard.[21] They formulated models for both uniform and non-uniform probability cases and for both nested and incremental benefit functions.

Both the expected-covering and weighted benefit expected-covering approaches require some information regarding the likelihood that a vehicle based at a facility will be busy. In Santo Domingo our research team did not have such information, as no real E.M.S. system was in operation.

Therefore, it made sense to try and extend the Daskin/Stern HOSC to incorporate weighted demand:

> Maximize the multiple coverage of demand within a pre-specified maximum travel time with the minimum number of vehicles.

Although we were not aware of it at the time, two groups had independently developed formulations for the back-up demand coverage problem. Those formulations of Benedict[22] and Hogan and ReVelle[23] are discussed below in relation to the Dominican ambulance deployment problem.

THE DOMINICAN AMBULANCE DEPLOYMENT PROBLEM

The Dominican ambulance deployment problem (D.A.D.P) seeks to maximize the multiple coverage of demand within a user-specified critical response time s, with the minimum number of facilities. The essence of the D.A.D.P. was finding a compromise among candidate locations which achieve three competing objectives: maximizing multiple coverage, minimizing the number of facilities, and minimizing the upper bound on response time under four system states—day and night traffic conditions during the work week and weekend. This can be translated into two formulations, one multi-objective and a second sequential optimization (see Figure 1 and Table 4).

The objective function (1) maximizes the weighted sum of two goals, the minimization of facilities and the maximization of multiple demand coverage. Constraint (2) states that a zone is multiple-covered only if a vehicle is located in zones such that more than one can cover zone i within s time units. Constraint (4) is the integrality constraint.

The sequential optimization formulation is introduced only as a means of efficiently testing a heuristic's performance (see below). The analyst first solves set covering: minimize selected sites [equation (5)], subject to the constraints that (a) a facility either is or is not at some site j [constraint

(A) *A Multi-objective Formulation*

$$\text{Minimize } Z_1 = W\sum_j X_j - \sum_i M_i a_i \qquad (1)$$

$$\text{subject to: } \sum_{j\in N_i} X_j - 1 \geqslant M_i \quad \text{for all } i \qquad (2)$$

$$M_i \geqslant 0 \quad \text{for all } i \qquad (3)$$

$$X_j = (0, 1) \quad \text{for all } j \qquad (4)$$

(B) *A Sequential Optimization Formulation*

Step 1: Set covering

$$\text{Minimize } Z_2 = \sum_j X_j \qquad (5)$$

$$\text{subject to: } \sum_{j\in N_i} X_j \geqslant 1 \quad \text{for all } j \qquad (6)$$

$$X_j = (0, 1) \quad \text{for all } j \qquad (7)$$

After finding Z_2, then proceed to step 2.

Step 2: Maximize multiple coverage

$$\text{Maximize } Z_3 = \sum_i Q_i a_i \qquad (8)$$

$$\text{subject to: } \sum_{j\in N_i} X_j - Q_i = 0 \quad \text{for all } i \qquad (9)$$

$$\sum_j X_j = Z_2 \qquad (10)$$

$$Q_i \geqslant 1 \quad \text{for all } i \qquad (11)$$

$$X_j = (0, 1) \quad \text{for all } j \qquad (12)$$

Note: Q_i in part (B) is equal to $M_i + 1$ in part (A).

FIG. 1. *The Dominican ambulance deployment problem.*

TABLE 4. *List of variables and information sources for the Dominican ambulance deployment problem*

Variable	Definition	Information: Requirements	Information: Source
X_j	A decision variable for ambulance stations, defined as 1 if a facility is located in zone j and 0 otherwise	Set of js, the potential facility sites	Centroids of census polygons
M_i, Q_i	Decision variables for back-up ambulances (note: $Q_i = M_i + 1$)	Set of demand areas i	Centroids of census polygons
a_i	Demand weight for zone i	Population of a census polygon	1981 Dominican census
N_i	The set of potential facility sites, where $N_i = \{j/d_{ji} \leqslant s\}$ and d_{ji} is travel time between j and i; s = upper bound on response time that defines coverage	Travel times among pairs of census polygon nodes for for 4 conditions: Weekday, Weeknight, Weekend day, Weekend night	Travel-time estimates made through this study

(7)] and (b) at least one facility be available to serve each source of demand within an upper limit on response time [constraint (6)]. The second step maximizes the sum of multiple coverage [equation (8)]. One constraint defines the number of facilities which cover node i as the frequency of coverage [constraint (9)]. Constraint (10) limits facilities to the number selected by set covering. Constraint (11) forces at least minimal coverage of all sources of demand by facilities.

The D.A.D.P. requires only three types of information: (a) zone populations (or some other surrogate for E.M.S. demand); (b) a zone-to-zone travel time matrix; and (c) an upper limit on response time. Table 4 lists the variables of these formulations and the data required to implement them.

The analyst can use the multi-objective formulation to explore a number of policy issues. For example, changing the coverage time s changes the set N_i of zones that can cover node i. By changing s, the user can analyse how changes in coverage time affect the degree of multiple coverage or the number of facility locations. The effect of preferences for (or against) specific sites can be analysed by setting the corresponding X_j values to 1 (or 0). The resulting population coverage can then be compared with that which results from the unconstrained case to assess the opportunity cost of site preferences.

Benedict independently developed a back-up coverage model which is nearly identical to the D.A.D.P.[22] One difference is that Benedict may define X_j in a more general way as the number of vehicles located at node j. This difference should be important because one can often improve the multiple-cover objective by locating several vehicles at a single location.[24]

Hogan and ReVelle independently formulated a model which trades off population that has one-facility coverage (one server within the distance standard) against population that enjoys two-facility coverage or double coverage (two servers within the distance standard).[23] Their formulation protects against giving undue value to many covers of a single highly accessible point while some points get no second coverage.[25]

SOLUTION PROCEDURES

The investigators would have preferred to solve the D.A.D.P. using an integer programming code, but that was not a feasible option in the Dominican Republic. The SESPAS minicomputer, which might have had sufficient capacity to handle a problem in the 214 nodes, was no longer operational, falling victim to a dearth of foreign exchange for spare parts. Even if it had been working, no integer or even linear programming codes were available.

The only available microcomputer was a small Texas Instrument Pro (TI) with 128 kilobytes of random access memory. No commercial integer or linear programming code which could be operated on the TI was available. If one had been available, it could not have had the capacity to solve the Santo Domingo problem with 214 potential facility sites and 214 sources of demand.

We solved this problem by developing a multi-objective heuristic that could simultaneously minimize the number of facilities, maximize multiple coverage, and minimize response time. Figure 2 illustrates the steps of the heuristic.

The first step is to generate a cover matrix from one of a user-supplied set of response time goals and the matrix of travel times among node pairs for the 214 census polygons in Santo Domingo.

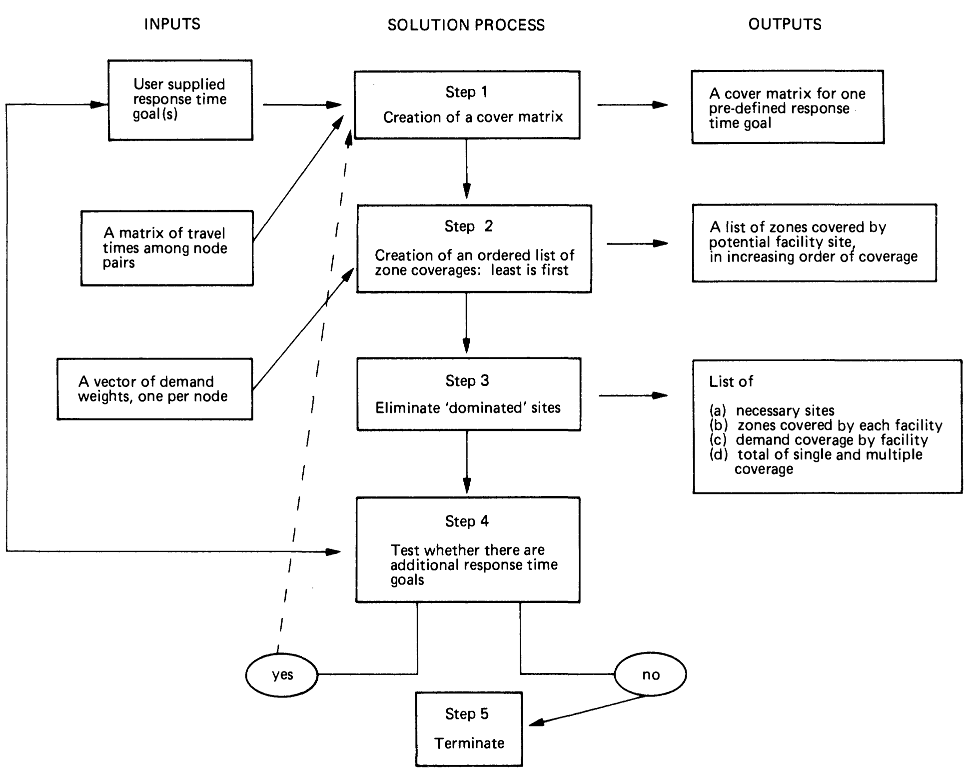


FIG. 2. *Steps in the D.A.D.P. solution procedure.*

For each facility, it is possible to compute total demand coverage by multiplying the (0, 1) coverage vector by the vector of demand weights. The 214 potential feasible sites can then be ordered by the rank order of total demand coverage. The node which covers least demand within the time limit becomes No. 1, and the node which can cover the largest fraction of demand on its own is defined as No. 214.

Step 3 is the elimination of 'dominated' sites. Beginning with No. 1, the node with the smallest potential coverage, we ask:

> Can each demand zone covered by this facility be reached by another facility within the maximal response time?

A node is called 'not necessary' or 'dominated' when all the zones which it can serve can also be served by at least one other facility. A dominated facility site is eliminated from consideration. In other words, the decision variable (column) is eliminated and there is a reduced matrix. The process begins again with the next zone in order of smallest coverage.

At some point there will be a potential facility that is not dominated. In other words, if it were eliminated from consideration, then some demand zone would not be covered by any other potential facility site. The collection of such non-dominated sites constitutes a set from which the heuristic will select a solution (see Appendix). The heuristic selects those facility sites with the largest total coverage by (a) deferring their elimination and (b) selecting as a solution the non-dominated locations which maximize multiple coverage.

This heuristic could be called "Strangelovian selection of the fittest". In the movie "*Dr Strangelove*", the military leaders on both sides were not too upset about going to war. Their privileged positions allowed them to postpone death by moving to underground cities built for the powerful few. So too, this heuristic allows a site with naturally broad coverage to have an enhanced likelihood of selection into the solution as a facility site. Sites are selected to provide service to all and yet maximize the sum of all multiple coverage.

If there is only one maximal response time, the algorithm terminates after a solution is found. If there are alternate upper bounds on response time, the process begins again with the generation of a new cover matrix.

The heuristic generates multi-objective trade-offs with a small number of iterations. For any defined period of day or any of four options of maximum response time, the heuristic generates a minimum facility solution that covers all demand and provides maximum multiple coverage. Thus the number of solutions required to generate a trade-off surface is computed by the product of the number of system travel states and limits on response time.

It is beyond the scope of this paper to fully evaluate the 'Strangelovian heuristic'. Heuristic results were compared to integer programming solutions using the M.P.S.X. linear/integer programming code on an I.B.M. 4341 at The University of Texas at Austin. The relaxed form of the two-step formulation was solved to test the heuristic performance in terms of each objective's optimum. Branch and bound procedures were used to resolve fractional solutions. The heuristic works well for complex coverage matrices, where a number of potential facility sites can cover a source of demand. In such cases, the heuristic generates answers which are optimal in terms of both 'minimize facility sites' and 'maximize multiple coverage' objectives. As the cover matrix becomes more sparse—with many zero elements and few ones—its performance along both objectives degrades below optimality. The following section discusses illustrative solution-times and heuristic performance.

RESULTS

We solved the heuristic for four times of day (weekday, weeknight, weekend day and weekend night) and 19 maximal response time standards (from 2 to 20 minutes). Each of the 76 solutions covers all the population in Santo Domingo within a user-defined maximum service-time standard. Each solution represents the minimum number of facilities which cover all nodes (for given time-of-day and maximum response time). In addition, each solution finds a heuristic optimum for the maximum 'sum of the multiple coverage' problem. For each case the results included:

a list of potential ambulance sites;
the list of demand zones covered by each facility (within periods ranging from 1 minute to the response time standard); and
data on the number and location of zones which are accessible to 1, 2, . . . , *n* facility sites within the time standard.

Table 5 illustrates the types of output generated by the heuristic.

Table 6 illustrates policy-related results for a 5-minute response-time weekday solution. A large fraction of the population can be multiple-covered by as many as six facilities within 5 minutes. If multiple-covered populations are counted each time they are covered, then the 'total coverage' exceeds 100%.

Figure 3 illustrates how response time affects both coverage and the number of vehicles for the workday shift (7:00 a.m.–7:00 p.m. weekdays). As the upper limit on coverage is relaxed from 5 to 10 minutes, fewer vehicles are required; only 8 vehicles can reach all of Santo Domingo in 10 minutes, while 23 are required for coverage in 5 minutes. The degree of multiple coverage varies in no functional way; each coverage solution represents the heuristic's local optimum for multiple coverage given the number of vehicles.

Figure 4 shows how different time periods affect the results. Recall that four travel-time matrices were developed to incorporate various degrees of congestion—weekdays, weeknights, weekend days and weekend nights. We expected to find that a larger number of vehicles are required to cover

TABLE 5. *Illustrative heuristic results based upon a solution for weekday coverage within 5 minutes*

(A) *Zone Coverage Results*—Vehicle Sited at Node 12
11 nodes covered (5.14% of all nodes):
4, 6, 7, 8, 10, 11, 12, 14, 15, 16, 30

(B) *Population Coverage Results*—Vehicle Sited at Node 12

	Population covered	
Response time	Persons	% of city
1	6453	0.50
2	10,664	0.82
3	37,569	2.90
4	43,010	3.32
5	68,719	5.30

(C) *Multiple Coverage of Demand* at Node 7

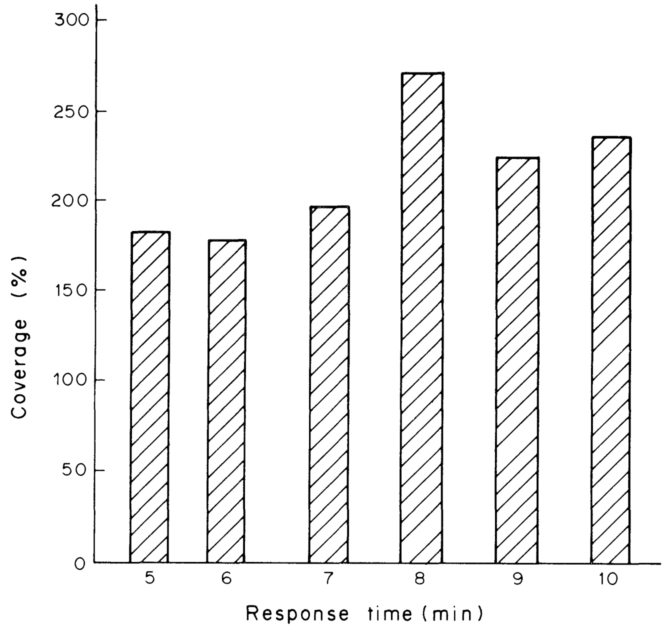
Response time	Sites which cover in 5 minutes
1	
2	12
3	12, 15
4	12, 15
5	12, 15, 16

TABLE 6. *Maximum multiple coverage pattern for 5-minute solution (7:00 a.m.–7:00 p.m. shift, normal days)*

Degree of multiple coverage	Zones covered		Population covered*	
Number of ambulances	Number	%	Number	%
1	54	25.2	304,316	23.4
2	69	32.2	825,084	63.4
3	66	30.8	1,231,863	94.7
4	21	9.8	583,372	44.9
5	3	1.4	107,225	8.2
6	1	0.5	33,930	2.6
Total	214	99.9†	3,085,790	237.3

*Population covered = (population of node) × (number of times covered). For example, node 107 is covered six times: thus the population coverage is (5655) (6) = 33,930. As the total population of Santo Domingo is 1,300,422, any number above this figure represents greater than 100% coverage.

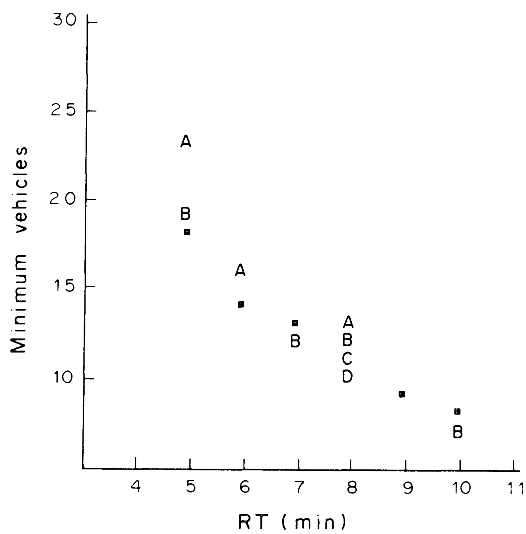
†Items may not add to 100% owing to rounding off of significant digits.



Response time (min)	Coverage† (%)	Number of vehicles
5	178.04	23
6	174.77	16
7	195.79	13
8	270.56	13
9	224.30	9
10	236.45	8

†% population coverage provided by heuristic.

FIG. 3. *Population coverage for Santo Domingo, weekdays.*



Response time (RT)	Vehicles*			
	A	B	C	D
5	23	19	18	18
6	16	14	14	14
7	13	12	13	13
8	13	12	11	10
9	9	9	9	9
10	8	7	8	8

FIG. 4. *Minimum vehicles vs response time, Santo Domingo.*A—weekdays; B—weeknights; C—weekend days; D—weekend nights; ■—any combination of A to D.*

Santo Domingo in a congested period (a weekday) versus a less congested period, such as a weekend night.

For a 5-minute response, this relationship holds. Twenty-three vehicles can reach all of Santo Domingo in a weekday. Only 18 are required to cover the city on weekend days or nights. For an 8-minute response time, each reduction in congestion from weekday to weekend night results in a lower number of required vehicles.

However, congestion appears to make no difference for service within 9 minutes. We found that 9 vehicles cover all Santo Domingo using all four travel-time matrices.

After the computer analyses were completed, the Minister of Health decided that one run would provide the basis for a final selection of E.M.S. vehicles sites. This solution was the minimum number of sites which maximize multiple coverage within a 5-minute response time, based upon a travel-time matrix representing conditions during a normal workday. SESPAS selected a 5-minute bound on response time because it has a medical meaning for trauma and it has been used as a standard for recent E.M.S. facility planning in the United States.[26] The normal weekday was selected as the design travel-time because all other periods are less congested; hence this solution underestimates multiple coverage of demand by vehicle facilities at other times. SESPAS staff recognized that tactical vehicle relocation[27–29] could be used for shifting vehicles to respond to different patterns of emergency medical demands that might develop during the other three periods.

IMPLEMENTATION PLANS

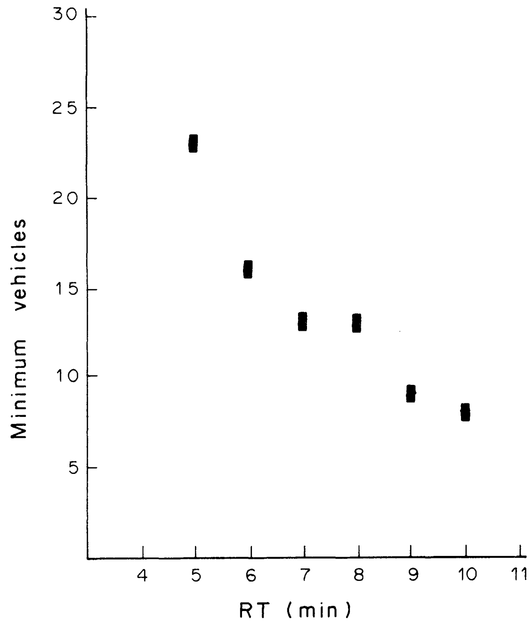
The 80 ambulances arrived in the Dominican Republic during the fall of 1984. A portion of these gradually will be deployed around the metropolitan area of Santo Domingo. SESPAS will use the 5-minute workday base case to initiate deployment. They will then attempt to generate demand for the system by a campaign of media advertisement. It is likely that some shifts in the E.M.S. stations will occur, based upon patterns of expressed demands for emergency medical care that arise. Computer solutions for five other runs (for the 6-, 7-, 8-, 9- and 10-minute workday cases) will be consulted, depending upon (a) the pattern and strength of demand and (b) experience with E.M.S. operating costs.

Figure 5 is a trade-off curve for these six solutions. It illustrates how a reduction of the maximum response-time standard forces an increase in the number of vehicles. The final deployment will thus have between 8 and 23 vehicles, covering demands within a range of 5–10 minutes. SESPAS wishes to remain flexible prior to facility construction so that it will be able to afford and operate the system it adopts.

Three other components of the emergency medical system are being implemented simultaneously —a communications system, emergency room improvements in four major hospitals, and a community education programme. A 24-hour radio dispatch system has been established; it will eventually operate in conjunction with a telephone-based E.M.S. vehicles dispatch system. The Ministry of Health is upgrading emergency rooms in the four major public hospitals in Santo Domingo to (a) provide modern sanitary in-patient and surgical areas, (b) equip the facilities with advanced life-support equipment and medicines and (c) staff them with emergency physicians. A major effort will be initiated to train citizens in first-aid skills and educate the general population about the availability and intent of the E.M.S. system.

BENEFITS

The principal benefit of this project is that it has provided SESPAS with a basis for establishing a modern emergency medical service system in Santo Domingo; SESPAS will soon deploy vehicles. SESPAS' coordinated improvements in 'urgency care' (public education, pre-hospital aid and hospital medical care) should reduce the likelihood of unnecessary trauma deaths in Santo Domingo.



Response time (RT)	Minimum vehicles
5	23
6	16
7	13
8	13
9	9
10	8

FIG. 5. *Minimum vehicles vs response time, Santo Domingo, weekdays.*

A second collateral benefit is the impact of this project on the medical profession in the Dominican Republic. According to the Minister of Health:

> The current medical system in the Dominican Republic has elements of corruption, incompetence, and wastefulness; it is often unproductive and self-serving. The importance of the emergency and urgency care system is that it will allow us to introduce a destabilizing element into the system, competent and appropriate medical care for urgent cases. When the Dominican people see the difference between what they have been used to and what can be done, it will help reform the entire system.

To illustrate the problem, there exists a physician regulation in the Dominican Republic which limits doctors' working hours to the period of 8 a.m. to noon. This restriction means that only interns, students and nurses are on duty in many hospitals in the Dominican Republic for 20 hours of any given day. Field surveys of rural clinics and rural hospitals found that some doctors were absent from even these restricted work hours on a regular basis.[30] The advent of the ambulances provides a pretext to retrain unemployed young physicians in emergency medicine. These persons, if deployed in ambulances and emergency rooms throughout Santo Domingo, can improve significantly the quality of delivered medical care.

Another benefit resulting from this study process has been the spirit of confidence in management science techniques that has developed at SESPAS. During the summer of 1984, SESPAS staff worked with University of Texas colleagues to develop ambulance location plans for the Republic's second largest city, Santiago. The confidence in operational research techniques has been enhanced by the primary role of Dominican participants in this research. Ricardo Lantigua developed the approach for estimating travel times among polygons. Hector Sánchez developed the heuristic described in the Appendix.

A final benefit of this research is its assistance to SESPAS in achieving the Minister's health sector reform agenda:

> A system which responds to urgent medical cases is a cancer for the Dominican health system. It is a foreign growth that undermines otherwise ultra-stable institutions which do not provide medical care. E.M.S. is viewed by developed nations as a difficult innovation. We can show that an inexpensive and small-scale 'urgency care' system can help people. Its existence will undermine claims of existing institutions that significant additional funds and personnel are a prerequisite for the delivery of medical services.

The ambulance system performed in such a 'destabilizing' role in the spring of 1985. Physicians in Santo Domingo struck for higher wages and left their hospital posts. According to observers, the hospital supervisors and staff at military hospitals alone would have been unable to cope with the medical case-load. The ambulances and their paramedic physicians provided mobile emergency care and transport. As a result, the physicians were forced to settle the strike without achieving the pay raise.

CONCLUSIONS

A recent comprehensive review of the use of location-allocation models for improving the accessibility of services in developing countries did not report any examples of implemented operational research for ambulance deployment in urban areas in the Third World.[31] This project demonstrates the feasibility of transferring location-allocation techniques for delivering public services in these nations. This paper has described the development, use and implementation of systems techniques for determining ambulance deployment. The government of the Dominican Republic is using these methods as an adjunct to common-sense judgement to evaluate the opportunity costs of a number of alternative vehicle locations. Results from this project have provided the Ministry of Health with a rationale for emergency medical service innovations in that nation's capital.

APPENDIX

Operation of the 'Strangelovian' Heuristic

The multi-objective optimization step of the heuristic used to solve the Dominican ambulance deployment problem is the 'Strangelovian selection of the fittest'. In this step, a matrix that indicates the facilities accessible to which sources of demand within the maximal response time (a cover matrix) is used to eliminate 'dominated' potential ambulance sites.

A node is 'dominated' when all the zones which it can serve can also be served by at least one other facility. A zone is not dominated if its elimination from the solution set would leave some source of demand without coverage. Any dominated zone is eliminated and any non-dominated zone is included in the solution set.

Zones are tested for domination in order of 'total coverage'. The zone which covers the smallest fraction of demand is considered first, and the zone which is accessible to the largest fraction of demand is tested last. This procedure assures that all zones will be covered. It also defers elimination (and enhances the likelihood of selection) of potential facility sites which can cover a large fraction of the demand.

Consider Table A1, an 8-node cover matrix that can illustrate the operation of the heuristic. The central matrix shows which sites j can cover which sources of demand. For example, potential facility sites 1 can cover all origins of demand except for origin 4.

TABLE A1. *An example solution of the Strangelovian heuristic*

		Potential facility sites (j)								Population at site i
		1	2	3	4	5	6	7	8	
Demand origins (i)	1	1	1	1	0	1	1	1	1	21
	2	1	1	1	1	1	1	1	0	15
	3	1	1	1	1	0	0	0	0	8
	4	0	1	1	1	0	0	0	0	6
	5	1	1	0	0	1	1	0	1	17
	6	1	1	0	0	1	1	1	1	26
	7	1	1	0	0	0	1	1	0	30
	8	1	0	0	0	1	1	0	1	25
Total population covered by facility		142	123	50	29	104	134	92	89	
Rank (smallest coverage is No. 1)		8	6	2	1	5	7	4	3	
Example of alternative coverage		—	—	No. 2	No. 2	No. 1	No. 1	No. 2	No. 1	

TABLE A2. *Reduced matrix*

	Potential facilities		
Demands	1	2	6
1	1	1	1
2	1	1	1
3	1	1	0
4	0	1	0
5	1	1	1
6	1	1	1
7	1	1	1
8	1	0	1
Rank	8	6	7
Total coverage	142	123	134

The total population covered by any facility j is computed by multiplying the coverage vector by the population vector. The total coverage of site 1 is thus $21 + 15 + 8 + 17 + 26 + 30 + 25 = 142$. Total coverage figures can be ranked in order of coverage. As facility site 1 covers the largest fraction of demand, it is the 8th in order.

Beginning with potential facility site 4 (rank 1), perform the following dominance test:

> Can each demand zone covered by this facility be reached by another facility within the maximal response time?

A test of node 4 indicates that each demand site that it covers is accessible from a number of the other potential facility sites which can cover a larger fraction of the population. For example, node 4 reaches origins 2, 3 and 4. Node 2 also reaches each of these origins, and more in addition. Thus node 4 is dominated by node 2. A dominated column is eliminated from the matrix, and the process starts again.

In this example, after five iterations, the matrix would be reduced to Table A2. Node 2 is not dominated because, if it were eliminated, demand 4 could not be served. A facility must be sited at node 2. Node 6 is dominated by node 1, as each demand locus served by 6 is also served by 1. Node 1 is selected because it covers a larger fraction of demand. In this case the solution set would be nodes 1 and 2. The solution represents the minimum number of sites needed to cover all demand. The Strangelovian procedure also screens the alternative optima to find that set of two which maximizes multiple coverage of demand.

Previous investigators have developed heuristics which eliminate dominated zones as part of the solution procedure.[32,33] One distinctive element of the Strangelovian procedure is the rank ordering of decision variables by the sum of multiple coverages, which allows the single solution to approximate a multi-objective optimum.

Acknowledgements—This project was suggested by Dr Antonio Ugalde and was carried to fruition through the support of the Minister of Health of the Dominican Republic, Amiro Pérez Mera, M.D. The Pan American Health Organization, the U.S. Department of Education, the Lyndon Baines Johnson Foundation and the University Research Institute of The University of Texas at Austin funded this research. We acknowledge the contributions of the following persons associated with SESPAS or The University of Texas at Austin: Ing. Dilzo de los Santos, Ing. Rafael Vásquez, Melvin Andújar Cairo, M.D., Glen Jansma and Lisa Nungesser. Professors Antonio Ugalde, Chandler Stolp and Robert Greene of The University of Texas at Austin, Sharon Ugalde of Southwest Texas State University, Richard Church of the University of California at Santa Barbara, Charles ReVelle of The Johns Hopkins University, Alfonso Casasnovas and Manuel Bonilla of Santo Domingo provided constructive comments. The authors are particularly grateful to Amiro Pérez Mera, M.D., SESPAS Health Minister, and Professor Mark Daskin of Northwestern University for allowing us to include in this paper their remarks and insights.

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