SIMULATION STUDY OF A HOSPITAL EMERGENCY COMMAND SYSTEM

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Abstract

Hospitals vary greatly in organization, physical layout and size, staffing, and equipment. However, they share common problems when they attempt to respond effectively to the demands of clinical emergencies. This paper addresses the mathematical modeling, system analysis and design along with supportive statistical analyses utilized to define hospital response capabilities to the demands of clinical emergencies and to evaluate the potential benefit to be gained from an automated communications system known as the Hospital Emergency Command System (HECS). A computer simulation of the system operation in its actual environment has been developed for emergency situations such as cardiopulmonary arrest in any location, surgical emergencies originating in the accident ward, and civil disasters with major influxes of acutely injured persons. In addition, a parallel simulation has been developed which permits evaluation of a hospital's present emergency care response capabilities. The simulation program has been prepared in a modular manner permitting evaluation of a wide variety of hospital configurations and emergency mobilization approaches. A comparison is made of the time required to bring appropriate medical care to the patient before and after HECS is in operation.

1. INTRODUCTION

The inadequacy of emergency care in hospitals throughout the United States has received much attention recently. The lack of consistency, organization and immediacy in mobilizing the emergency resources within the hospital prevents timely response to a majority of clinical emergencies, such as:

- Cardiopulmonary Arrest
- Surgical Emergency (originating in the accident ward)
- Civil Disaster (or major influx of acutely injured patients)

Determination of the weaknesses of current hospital techniques has been made by the staff of The Emergency Care Research Institute. The following description(1) of a typical resuscitation episode was compiled from more than 400 individual events studied at various hospitals:

A nurse discovers a pulseless and apneic patient and immediately institutes mouth-to-mouth respiration and external cardiac compression. She waits 19 seconds (range, 5 to 112 seconds) after dialing for the telephone operator to answer. During this period she is diverted from her basic role of supporting the patient. The operator triple pages the emergency code every 20 seconds. The time elapsed from initial dialing by the nurse to hearing the first page is 31 seconds. The emergency cart arrives 175 seconds after initial dialing. Of this 175 seconds, 31 is due to telephone and paging lag. Five to seven physicians and nurses are present in the patient's room 148 seconds after dialing.

At night the situation is considerably worse. A single telephone operator must page and notify individual house staff on-call rooms. The notification procedure alone increases from 31 seconds to over two minutes. During this period, of course, the switchboard sustains no other functions.

In our limited study of human errors in two urban hospitals, the telephone operator erred by giving no room location or the wrong room location four times in a series of 58 real resuscitation alerts. This closely approximates the experience of other hospitals.

With surgical emergencies, time is often less critical but organization becomes a major problem.

Similar patterns in obstetrical emergencies and civil disasters involving mass accidents with a large influx of acutely injured persons have also indicated that the elements of time and organization are interrelated and critical.(1)

A Hospital Emergency Command System (HECS) has been proposed for installation in existing or new hospitals as a means of applying technology to provide "fail-safe and errorless" communication and resource dispatching. Since a relatively consistent set of responses are required for the emergency categories previously listed, an integrated electromechanical system would inherently permit an organized, timely and accurate means of response. The HECS configuration is illustrated in Fig. 1.

Subsequent sections of this paper address the mathematical modeling, system analysis and design along with supportive statistical analyses and baseline data acquisition utilized to define existing conditions within the hospital and to evaluate the potential benefit to be gained from the HECS. A computer simulation of the system operation in its actual environment is discussed as well as a parallel simulation which permits evaluation of a hospital's present emergency care response capabilities.

2. THE IN-HOSPITAL EMERGENCY ENVIRONMENT

The clinical significance of the time element in responding to in-hospital emergencies has prompted its use as a yardstick in the simulation study. That is, the critical variable is the time to deliver appropriate medical personnel and equipment to support the emergency patient. This time interval is composed of a number of mission-related sub-intervals, which are defined in Fig. 2. A prevalent characteristic of all of these time values is their randomness, and therefore it is appropriate to describe them by probability distributions. The mission profile has also been divided into a number of Phases which provided the most convenient framework for modeling the in-hospital emergency environment.

Any response to clinical emergencies within the hospital must provide control and mobilization in four areas (see Ref. 1):

(1) <u>Communications</u> (telephones, public address, pocket page system, visual page).

(2) <u>Personnel</u> (physicians, nurses and technicians on the general floors, in laboratories, offices, on-call rooms and homes).

(3) <u>Equipment</u> (emergency carts or cases with a broad variety of drugs and equipment).

(4) <u>Mobility</u> (elevators, doors, corridors, etc.).

To varying degrees, each of these elements are involved (in a relatively specific manner) in the five phases of an in-hospital emergency. These phases, shown in Fig. 2, exist with or without HECS, but their time values may be different. Each of these phases is discussed in what follows with regard to the actual hospital environment. These scenarios aid in model formulation, data collection specification and computer simulation program development.

2.1 DETECT PHASE

This is the phase where someone in the hospital discovers that an emergency situation exists. This phase depends entirely on people, except when the patient is continually instrumented, as in some cardiac care units. The kind of person who finds a patient in cardiac arrest may be untrained, may be part of the alerting agency in the hospital, or may possess high medical competence. We can list several kinds of people who may be the ones to detect an arrest. They are, in increasing order of the amount of medical training they may have:

(1) Outside visitors or another patient

(2) Non-medical hospital personnel

(3) Orderlies and aids

(4) Licensed Practical Nurse

(5) Registered Nurse

(6) Physicians

    (a) Not on hospital staff

    (b) On hospital staff

For the simulation, it would be useful to know the relative frequency with which these different groups of people actually discover cardiac arrests. However, we would expect these data to come only from Post-Alert Interviews which contain specific questions addressing this issue.

Three types of particular situations can arise in the process of placing an emergency call in the hospital (notification process). The first is the false alarm and the second is failure to detect the emergency until the patient is beyond medical help. The third is the situation in which inadequate information is transmitted to permit accurate identification of the location and type of emergency. These aspects are not considered in the simulation study, but have been examined and are being treated during the HECS implementation study.

The DETECT phase is also important to the simulation from the viewpoint of "generating" emergencies. For each event, we need to know date, time, location, and type of event. Extensive data for date, time, and location of cardiopulmonary arrests at several of the study hospitals were made available for this effort. It is interesting to note that in one hospital the data was obtained from telephone switchboard operator's log-book and at another hospital from medical team records. At several hospitals this information could only be generated from patient records and only for a limited number of emergency situations.

Examples of the arrest data collected on event occurrence are shown in Figs. 3 and 4 for a single hospital. The frequency of occurrence by specific locations of interest is presented in Fig. 3a and the results by specific hospital building and floor are given in Fig. 3b. Figure 4 graphically shows the frequency of occurrence by time of day. If this detail data were not available for other emergencies and/or hospitals, then appropriate random processes models could be used to generate the required case data.

2.2 DISPATCH PHASE

The DISPATCH phase is represented by two parts. First, the person who discovered the emergency event must alert the dispatch system. The dispatch system, manual or automatic, must then alert the team members and direct them to the site of the emergency. That is, the operations are:

- Alert the "system"
- "System" alerts the team

How these two events come about depends on the physical structure of the hospital and on the operating policy of the institution.

The alerting system, either the current hospital procedure (switchboard, PBX, operator) or HECS, must identify the type of emergency and location. Errors and time delays certainly occur in both systems, but the specific operational procedures associated with each approach are different and these differences must be modeled.

Once the "system" knows that there is an emergency, it must determine what kind of emergency it is and where the team must go. The task now is to call the proper emergency team and its members and give them the alerting message. Who is called and the contents of the message depends on the nature of the event and the time of day. The physical equipment also controls the procedure to use in the alert, manual or HECS.

There are two parts to this segment of DISPATCH, (a) attract the attention of the team member and, (b) give him the message. The means of attracting the attention of the team members are the following:

(1) Visual page
(2) Aural page
    (a) Public Address system
    (b) Tone signal
(3) Telephone
(4) Pocket page
    (a) Tone signal
    (b) Voice channel
(5) Messenger

Access to the alert message is more limited. The types of equipment usually used are the telephone, aural page, voice channel on pocket receiver, and messenger.

Field studies and surveys must be performed to evaluate the time delays and errors incurred in actual practice. Furthermore, the operating policies under HECS use must be examined to permit representable modeling of the modifications to existing practices at the hospital.

2.3 DEPLOY PHASE

In this phase, specific medical personnel must travel to the patient treatment location, special medical equipment and supplies must be obtained and transported to specified sites and other emergency team members must prepare certain facilities and equipment to render medical aid. DEPLOY ends when an "effective" clinical team is at the care-delivery site. In the case of cardiopulmonary arrests, this typically requires the presence of one or two trained physicians and a resusitation cart or equipment.

For any emergency, the team members must make successive trips along corridors, on stairs, and on elevators to reach the storage place of a piece of equipment and then another series of trips to the site of the event. In specific cases, the team member may be normally stationed near the equipment or may go from alert site to event site directly. The simulation model must then take into account the following types of problems:

(1) To get from a general point in the hospital to a fixed location (equipment storage site)
(2) To get from a fixed location to a general point (any possible patient location)

(3) To travel between two general points

In each case, there are many paths which the team member may choose. The decisions are a function of experience, layout of the hospital (buildings, corridors, elevators, stairways, etc.), and personal choice. The description of the transit of heavy equipment is more restrictive. The routes are even more deterministic under HECS operation since specific elevators would be under automatic control.

Extensive field studies have indicated that one of the significant delays in responding to in-hospital emergencies is due to the waiting time required to obtain elevator transportation for facilities and staff. Therefore, a data collection and evaluation effort was performed for obtaining statistical estimates of performance for current elevator operation and various alternative HECS operating policies. The results of these studies, using actual hospital environmental data, are presented here for a selected elevator bank (having three elevators).

The HECS operating alternatives have been programmed using basic elevator travel time data and the results of probability models analyzed and implemented in the simulation program. This program allows a number of different elevator bank configurations as well as a flexible scheme for specifying travel times. Also, a variety of selection rules may be specified in the case where HECS can command any of several elevators in a bank. A comparison of arrival time delays after alerting is shown in Fig. 5 for both current and HECS operation. It is expected that actual HECS operating results may differ by about 10 percent from those obtained here, due to the data and model uncertainties.

It should be noted that the data presented for current procedures does not include an allowance for the time delay incurred from announcement of the emergency until arrival at the elevator and depression of the elevator button (or insertion of the emergency operating key). This delay may vary considerably under current operations, but would not exist under HECS operation since elevator call is initiated about the same moment of emergency notification.

Modeling of the DEPLOY phase, as well as the phases discussed previously, requires an organized and selective collection of information. Table 1 illustrates an overall outline of the data collection requirements which were used in the study described herein. Most of the information can be obtained easily, whereas some of the elements require a heuristic modeling effort – these are discussed in subsequent sections of this paper.

2.4 DELIVER PHASE

This is the time period during which members of the emergency team are treating the patient(s). The time required may vary from minutes to several hours and depends upon the type of emergency and its severity as well as many other medical and environmental factors.

2.5 DISPERSE PHASE

This last phase occurs when the "emergency" is over and represents the time required to restore and return equipment to its standby location ready for the next event. Also, during this time period the emergency team members return to their normal activities.

The question of simultaneous emergencies must also be considered if the HECS is to be designed to meet such a contingency. Figure 6 illustrates the time between cardiac arrest emergencies at a selected hospital. In no instance did any two events occur less than ten minutes from each other. Also, we may infer from the figure that, for about 50% of the cases studied, the time between emergencies (of this class only) is about two days. Consideration of the other emergency situations HECS would handle must also be made. If HECS could not handle the multiple emergency event, it seems reasonable to expect that the current hospital procedure could be used as a back-up system. Only the case of non-multiple emergencies is treated in the simulation program.

3. COMPUTER SIMULATION PROGRAM DESIGN

Hospital Administrators and Medical Staff have several alternatives to evaluate in the utilization of special equipment and trained teams for response to in-hospital emergencies. There is a policy matter as to the number and type of team members and their training. The second is the capital investment in special treatment equipment and communication equipment used to alert the team and to help deploy the team to the site of the emergency. It is not enough for these managers to know that HECS equipment has worked in another hospital under some policy; they need to know the value of the device in their own environment, using a "custom-built" operating policy. The simulation developed aims at providing a flexible evaluation tool that permits decision making before hardware purchase and installation.

The simulation encompasses two main options denoted as the CURRENT and HECS approaches; each operates in the same hospital environment. Once an emergency has been detected, either system must use its "hardware" and "software" to carry out several tasks. They are:

- Notify the warning subsystem
- Alert the emergency team
- Determine the path for the team members to get to the emergency site.

The simulation program breaks each type of alerting mechanism down to elementary steps, as in a time-and-motion study. The program includes stochastic elements where they are appropriate.

The diverse nature of the stochastic elements of the problem dictated the use of simulation as the only tool which would lead to dependable results in a reasonable time. As the details show, the convolution integrals would be most difficult to evaluate, whereas the computer simulation gives large samples in a few minutes of computer time. Also, a wide variety of hospital configurations and policies can be accommodated.

In most simulations of complex human activities we find that the quality of data is spotty; this project was no exception. Within project time restrictions (this entire project was a two man-year effort) it was possible to get two years of history for the sites and times of specific emergencies and yet there was only sparse data on the time that it takes to push a resuscitation cart through the corridors. Information on elevator travel and response times was adequate, but HECS automatic control had to be modeled.

The locations and times of emergencies are read from cards punched from data furnished by the hospital. If this data was not available, it would have been necessary to devise a case-generator which would pick locations and times using an appropriate random process model.

The start of the response sequence centers around the dialing of the telephone and an answer by the alerting system. In the case of the HECS device, this operating cycle is fairly repeatable and includes dial time and the time for the recording to be made. When the alerting system involves human operators, the activity is more complex. The first action is the time that it takes to dial the PBX operator. While there was no actual data on the response times at the PBX board, the hospital personnel schedule showed the number of operators on duty during any shift. Since there is usually a line open to the board most of the time, it seemed reasonable to model the operator response by a delayed exponential distribution. The form of the probability distribution function for the delayed exponential is given by

$$p(t) = \begin{cases} 0 & 0 \le t \le a \\ k \exp[-k(t-a)] & a \le t \end{cases}$$

where the mean and standard deviations are both given by 1/k. The mean value for the exponential generating function was adjusted to take into account the service levels of each operating shift. Another factor in the response of the human operator was the time needed for her to log in the call to the PBX and to write down the information to pass on to the team members. Experiments showed that the time required was relatively constant for this element.

Having modeled the entry of a case into the alerting system, we next considered the timing in notifying the team and directing them to the site of the cardiac emergency. Again, there are differences between the automated situation and the completely manual system. Using the HECS equipment, the alert is sent over the public address system while the equipment is simultaneously ringing all the telephones on the emergency event warning list. For manual operation, the girl at the PBX board first calls a warning over the public address system and then calls the numbers on the warning list until all the team members have been notified. There is another complication in the manual system – when the operator is dialing, she cannot identify the lights on the board which refer to calls in answer to the public address summons. The simulation takes this into account and also treats the serial nature of the manual system operation. The model chosen for simulating these reductions in time response was a delayed exponential distribution. The delay assumed that it takes a fixed period of time from the time the telephone dialing starts until the person called starts to respond. The stochastic part of the process includes the time necessary to travel to the telephone from a remote location and to communicate the emergency message before responding to the emergency alert. The use of the particular stochastic models is based mainly on the criterion of "reasonableness" in comparison with timing data collected on individual phases of this event.

The time for all team members (doctors, nurses, equipment handlers, etc.) to travel along hospital corridors and through the passages between buildings is generally the same for the manual and the automatic systems. However, the goal was to simulate the entire emergency care notification and dispatching operation. Accordingly, the simulation includes means to model these similar travel times. For travel time between buildings, there was a stochastic delay superimposed on a base level travel time; the latter time was calculated from the hospital corridor geometry and average movement times for both equipment and personnel. Since there are frequent short random delays in any trip through the corridors, the simulation uses a log-normal sample to carry the weight of the travel times farther from the base level. A variable is said to have a logarithmic normal distribution if the logarithm of the variable is normally distributed. The resulting probability distribution function is(2)

$$p(t) = \frac{\log_{10} e}{\sigma t} \varphi(u) \qquad 0 < t < \infty$$

where

$$u = \frac{\log_{10} t - \log_{10} \xi}{\sigma} \quad \text{and} \quad \varphi(u) = \frac{1}{\sqrt{2\pi}} \exp[-u^2/2]$$

Reference 2 shows that the mode, median and mean of the random variable t are determined by

$$\text{mode:} \quad \log_{10} t = \log_{10} \xi - 2.3\sigma^2$$

$$\text{median:} \quad \log_{10} t = \log_{10} \xi$$

$$\text{mean:} \quad \log_{10} t = \log_{10} \xi + 1.2\sigma^2$$

The simulation of elevator travel presented a different problem from the single-floor travel time modeling. It is possible for the HECS equipment to control a number of elevators in several buildings. However, it may be desirable to control only one elevator for emergency equipment transport. The only stochastic variable is the location of the car when the HECS device commands it. Since this car is in use around the clock, a uniform distribution over the floors of the building has been used. Once HECS has acquired control, the delivery to the proper floor is deterministic. This algorithm was developed using published elevator performance data and actual statistics. Note that this situation is also representative of the case where the hospital has elevator operators, except for the delay in notification.

The control of automatic elevator cars under the current hospital alerting system was different. Here, the team members on the detail press the call button and wait for the car. A large body of data on the rate of response to the call button for the elevators in several buildings at various times throughout the day can be readily collected. The sample data collected fit the log-normal distribution extremely well. Standard statistical methods gave the proper means and variances for the various time periods.

The program to simulate both current and HECS operation has been written in FORTRAN IV. There were several reasons for chosing this language. Most important, it can be implemented readily on many computer systems with only minor changes. This is useful should one want to simulate cases from one hospital on a number of optional computers or if one desires to simulate different hospitals, geographically separated, on locally convenient systems. Also, the program consists of a main program and a number of subprogram modules. This simplified the original programming and debugging and also resulted in a more flexible simulation. At any time we can replace a subprogram module with a new version. The programmer need only write the new version in a form which is logically consistent with the rest of the program.

Figure 7 illustrates the design of the overall HECS and current operations simulation. Each one of the major routines is designed in accord with the actual in-hospital emergency environment and thorough analytic consideration. The entire program is initiated by tape or cards documenting a given sequence of emergency alerts or by using a statistical description in conjunction with a random number generator (Emergency List Routine). The Hospital Configuration Routine is used to translate the physical structure of the hospital to a set of tables describing the transit times between any two important staff, equipment or department locations. Actual physical design constraints are also accounted for. The Staff and Equipment Routine is intended to permit a description of the expected locations, as a function of time of day and day of week, for all members of the professional staff and equipment pertinent to any one of the possible emergency conditions. The Elevator Routine provides the information necessary in estimating the travel time incurred in using any of the hospital's elevators, for equipment or staff transportation, during the course of an emergency. This routine is depicted in Fig. 8 in its verbal form. The Alert Routine is incorporated to reflect the policies or operational procedures for carrying out any of the subject emergency alerts, as presently adopted by the hospital and under HECS control. The Care-Time Routine is used to collect the actual time required to deliver each element of appropriate medical care to the patient for both the pre- and post-HECS installed conditions. Summary statistics are also computed within this module. Some details of specific aspects of the simulation program are discussed in what follows.

The Input Data Routine provides control over placing all information (data, parameter values, selection rules, indices, etc.) in the appropriate subroutine description matrices. An example of the form of these information arrays is the alert table which lists the team members and equipment selection rules for each emergency category. The Hospital Configuration Routine maintains several arrays one of which specifies the inter-building travel times for the situation in which a hospital complex has several buildings. Wherever necessary, these arrays are stored for both current hospital procedures and HECS so that the computation subroutines can access the data pertinent to the particular case. The Executive Routine provides overall program control and performs the necessary data transfer from one subroutine to another. As time delay information is computed for each of the personnel and equipment elements, the data is transferred to the Care-Time Routine.

The simulation development effort and experimental results were generated on the IBM360-75 via Remote Job Entry from a TASC based IBM 1130. This provided an on-site capability for a program requiring significant computer storage. The ability to maintain all the data arrays in computer core during a simulation run permitted economical use of computer time. Of course, the core requirements and run time are a complex function of the hospital configuration, operational policies, and the number of cases treated, as well as other less important parameters. But, the results for the current and HECS case (under the conditions of a single emergency category) for a large urban hospital required less than 100K bytes of core and less than 3 minutes to execute. This actual sample situation is treated in detail in the following section.

4. ACTUAL SIMULATION EXAMPLE

The computer simulation of the full scale operating systems must be keyed to baseline data gathered on the existing conditions within the hospital. It is important to obtain this data so that a valid comparison may be made of the time required to bring appropriate medical care to the patient before and after HECS is in operation. Without such an approach, justification for the HECS becomes theoretical rather than proven.

The simulation example chosen is for a large urban hospital having four major buildings. The emergency event data used was obtained from hospital records only for the case of cardiopulmonary arrests occuring within the hospital (this is the same data illustrated earlier in the paper). Since no information could practically be obtained for the detection delay time, the main objective was to establish the system response times (see Fig. 2). The team data used was:

MD1 - located on the 3rd floor of Y building

MD2 - located on the 5th floor of X building

Emergency CART: located on the 3rd floor of X building

It was assumed that only one of the three elevator cars in the X building would be under HECS control, whereas all other ones operate under the current system. In simulating the elevator delays, the data presented in the previous section is used including appropriate adjustments for the time of day of the emergency. In addition, the elevators in the Y, Z, and W buildings are much older and assumed 20% slower than the cars in the X building. This gives an average rate of travel of 0.13 minutes per floor for the X building and 0.16 minutes per floor for the others.

The total delay which the team experiences in servicing a call has three major parts, Alert Delay, Corridor Delay, and Elevator Delay. Each of these has fixed and variable parts. The variable parts are either deterministic (e.g., elevator travel speed from floor to floor) or stochastic (e.g., waiting for an elevator). Table 2 lists the Alert Delay budget and mathematical models used. Travel times in corridors and between buildings are not fixed. These figures are given as random trials, but always in excess of a minimum time. We do assume that travel time distributions in corridors are the same in all buildings. That is, corridor delay is independent of the building and independent of HECS. Travel on one floor of a building is a sample from a log-normal distribution with a mean of 30 sec and coefficient of variation 1.36. We do not use constant travel times, because obstructions slow down corridor travel speeds in a random manner. An exponential distribution would tend to concentrate simulated cases close to the elevators. To offset these factors and to prevent negative travel times, we choose the log-normal distribution. With the parameter values assumed, less than 1% of the trips on a floor of a building take longer than one minute. When there is travel on two floors, each is an independent sample. There is a different constant base level time between pairs of buildings. Table 3 shows these inter-building travel times.

The computer simulation results for the total of two years of emergency cases, 229 cardiopulmonary arrests, is shown in Fig. 9 for current hospital operations and Fig. 10 for HECS operation. The term "Total Care" refers to the situation in which <u>both</u> MD's and the resuscitation cart are at the emergency site. The term "Partial Care" refers to the case when the cart and only <u>one</u> MD arrive. Summary results are also given in these figures in terms of the component delays defined previously. The balance between the corridor and elevator delay components under HECS operation indicates that further improvement in elevator control would not significantly influence the results in this hospital situation. This is also true of the alert delay component. Replication of each individual year of data, 1966 and 1967, and the total cases presented was excellent. These results have also been drawn to graphically illustrate the nature of the response time distribution for total and partial care – see Figs. 11 and 12. Single case summary reports may also be computer-generated and one is shown in Fig. 13 – the abbreviation CPA denotes that this is a cardiopulmonary arrest emergency.

The improvement in emergency response time afforded by the HECS approach can be readily inferred from these results; at least for the specific hospital and situation studied.

There are some features of the response curves that must be explained. Chief among these is the bimodal nature of the cumulative frequency distribution of response time. This is barely noticeable in the case of the Total Care curves, but strongly visible in the curves for Partial Care. When one examines the physical structure of the hospital and the locations of the team members in relation to the sites of the emergencies, the reason for the bimodality becomes apparent. Looking first at the Partial Care situation, we find the cart and one physician in the same building. Most of the cases are in two of the buildings. Therefore, there is a distribution of times to service the local building and a superimposed distribution of times to service the other building. The bimodality is partly disguised in the Total Care situation by the need to wait for the other physician in every case.

This does not mean that the variance of the distribution is increased. In fact, the need to wait for the last team member in order to have Total Care, makes the variability smaller. We can readily see this by a table of interdecile ranges – see Table 4. The interdecile range is defined as the difference between the 90th and 10th percentile values of the cumulative distribution functions given in Figs. 9 and 10. When distributions start to be markedly non-Gaussian, the standard deviation becomes quite inefficient as a measure of dispersion. On the other hand, some of the order statistics are quite efficient in this case. For that reason, we have chosen the interdecile range rather than the standard deviation. In both Partial Care and Total Care, HECS has reduced the variability by about one-third of the current system value.

5. SUMMARY

The in-hospital emergency simulation discussed herein has been prepared in a manner that readily permits evaluation of current procedures and HECS evaluation for any of the several thousand hospitals throughout the United States. As may be noted, the results for the situation of cardiopulmonary arrest emergencies are given in terms of response time as depicted in Fig. 2. This has been done since no reliable information is available on the time delay from occurrence to detection of this type of emergency. This is not necessarily true for the other classes of in-hospital emergencies that HECS can handle. Although response time is a fair means of comparing HECS and current operations, further clinical interpretation may be desirable. That is, even if HECS saved two minutes on the average beyond the current system, the total delay time may still not be acceptable with regard to patient care. Reference 1 considers the time element in the following manner:

> Consider the clinical significance of the time element alone in resuscitation. While the commonly accepted time period for irrevocable nervous system death to ensue following cessation of cardiac and respiratory activity is four minutes, this is an arbitrary and misleading figure. The time interval is frequently well under a minute in patients with compromised cerebral vasculature or with higher than normal ambient or patient temperatures. It depends on cardiac output, respiratory gas exchange and tissue oxygen uptake prior to arrest.
>
> It is not true that once a patient is being sustained by mouth-to-mouth breathing and external cardiac compression, time becomes a less critical factor. Under such conditions, cardiac output is approximately twenty percent of normal and blood pH decreases rapidly. It is infinitely harder to defibrillate the heart at the eighth or tenth minute post arrest than it is during the first or second minute. Pacemakers are almost worthless more than a minute or two post arrest. The more rapidly these therapeutic modalities are applied, the greater is the probability that they will achieve the desired effect. Elapsed time in resuscitation is an even more critical factor than is generally appreciated.(1)

Using the time criterion itself, the results obtained in the previous section could be compared as shown in Table 5. For the particular situation examined and available data, this presentation reveals almost a 100 percent improvement provided by HECS.

A somewhat different approach is illustrated in Fig. 14. If a statistical distribution model for the time interval between occurrence of a cardiac arrest and the occurrence of an irreversible patient clinical condition could be developed, then we could derive a hazard function representing the instantaneous probability of an irreversible condition as a function of elapsed time. Such a measure would show a variance among patients, but a hazard function zone could be developed to represent such a situation. A probabilistic measure of in-hospital emergency system effectiveness is suggested then by Fig. 14, which shows the cumulative distribution function of response time for both system approaches plotted against an increasing hazard function. The effectiveness measure is the probability (P_H) that a response system (provided by the HECS) will restore the patient to a viable condition before a critical hazard level (h_c) is reached. Note the difference in the effectiveness between HECS and the current operation. The model shows that, like most statistical problems of this type, it is not sufficient for the average response time ($\bar{t}$) to be less than the critical time (t_{h_c}); the dispersion of response times is also important.

The overall accuracy of the simulation results is currently being confirmed through actual demonstration projects at three large hospitals. In the ultimate analysis it is hoped that this simulation program promotes the goal of the Hospital Emergency Command System, namely providing decreased patient mortality and decreased central nervous system damage in survivors.

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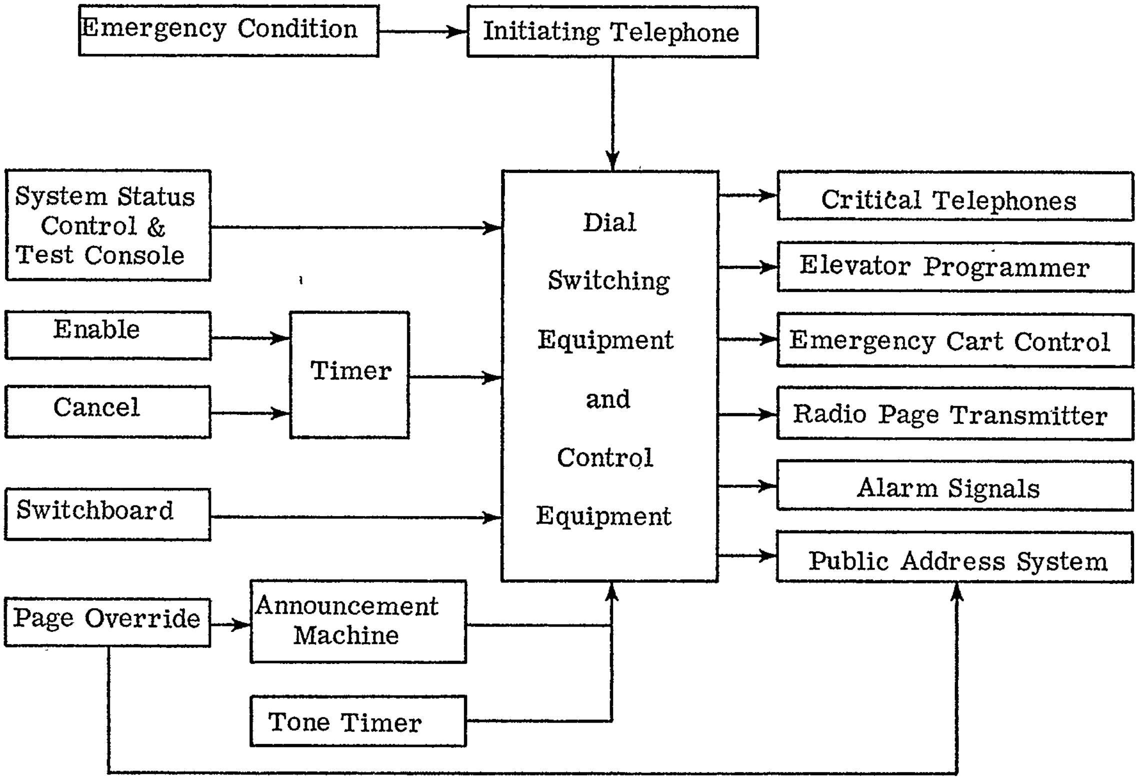


FIGURE 1. HOSPITAL EMERGENCY COMMAND SYSTEM (HECS)

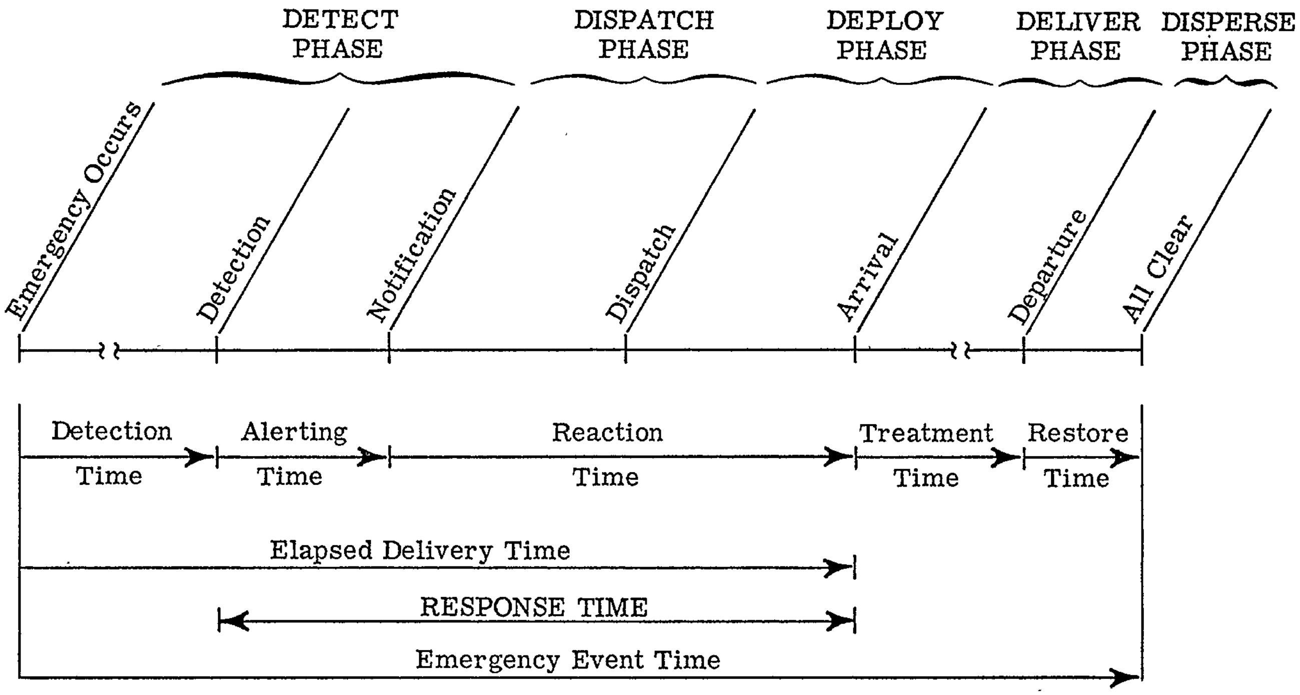


FIGURE 2. MODEL OF THE IN-HOSPITAL EMERGENCY MISSION PROFILE

```
LOCATIONS OF EMERGENCIES                     EMERGENCY LOCATIONS -- BY BUILDINGS

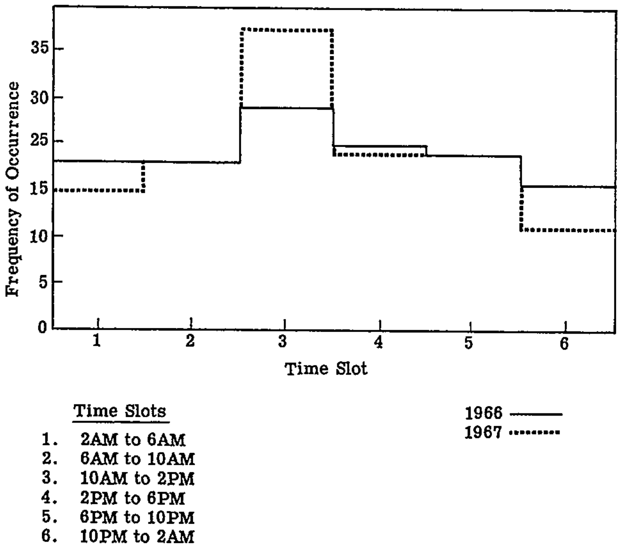
LOCATION  NUMBER OF CASES                    BUILDING  FLOOR  NUMBER OF CASES

   RW          27                               X        0          1
   ICU         28                               X        1          7
   W1          11                               X        3         30
   W3           9                               X        4          4
   XRAY         7                               X        5          2
   W8           2                               X        6          7
   DEL          1                               X        7          1
   RCOV         1
               86                               Y        2          5
OTHER LOCATIONS -- BY BUILDINGS                 Y        4          2
                                                Y        5          5
BUILDING  FLOOR  NUMBER OF CASES                Y        9          1

   X        3          2                        Z        1         11
   X        4          4                        Z        2         11
   X        5          2
   X        6          7                        W        1         27
   X        7          1                                          114
                                             NUMBER OF LOCATIONS NOT IDENTIFIED = 0
   Y        2          5
   Y        4          2
   Y        5          5
                      28
```

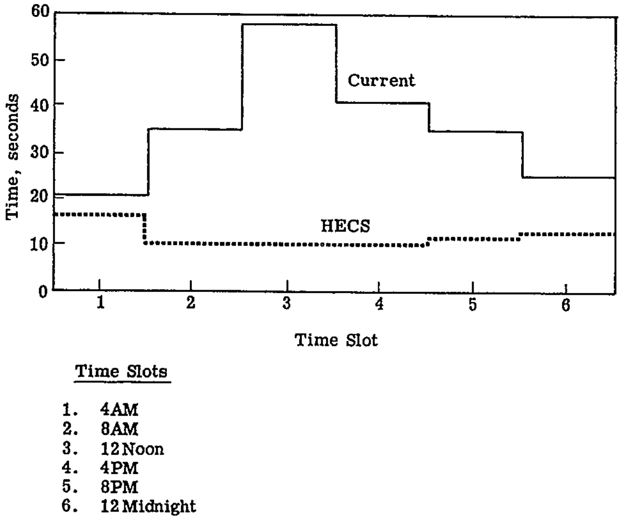
(a) (b)

FIGURE 3. IN-HOSPITAL EMERGENCY LOCATIONS AND FREQUENCY



Time Slots
1. 2AM to 6AM
2. 6AM to 10AM
3. 10AM to 2PM
4. 2PM to 6PM
5. 6PM to 10PM
6. 10PM to 2AM

FIGURE 4. FREQUENCY OF OCCURRENCE



Time Slots
1. 4AM
2. 8AM
3. 12 Noon
4. 4PM
5. 8PM
6. 12 Midnight

FIGURE 5. COMPARISON OF MEAN ELEVATOR ARRIVAL TIME FOR CURRENT AND HECS OPERATIONS

TABLE 1
SIMULATION DATA COLLECTION REQUIREMENTS

Information Element	Hospital Name					
	Current Procedures			HECS-Operation		
	Cardiac Arrest	Surgical Emergency	Major Patient Influx	Cardiac Arrest	Surgical Emergency	Major Patient Influx
Incident Survey (when, where)						
Detection Survey (who)						
False Alarm Survey						
Failures to Detect						
System Alert Procedures						
PBX Operator						
Alerting Equipment						
Alerting Message						
Alert Error Survey						
Emergency Team Procedures						
Equipment						
Medical Personnel						
Other Personnel						
Team Staffing and Location Survey						
Team Travel Survey						
Hospital Configuration Survey						
Buildings						
Elevators						
Equipment Storage						
Supplies Storage						
Communications						
Treatment Sites						

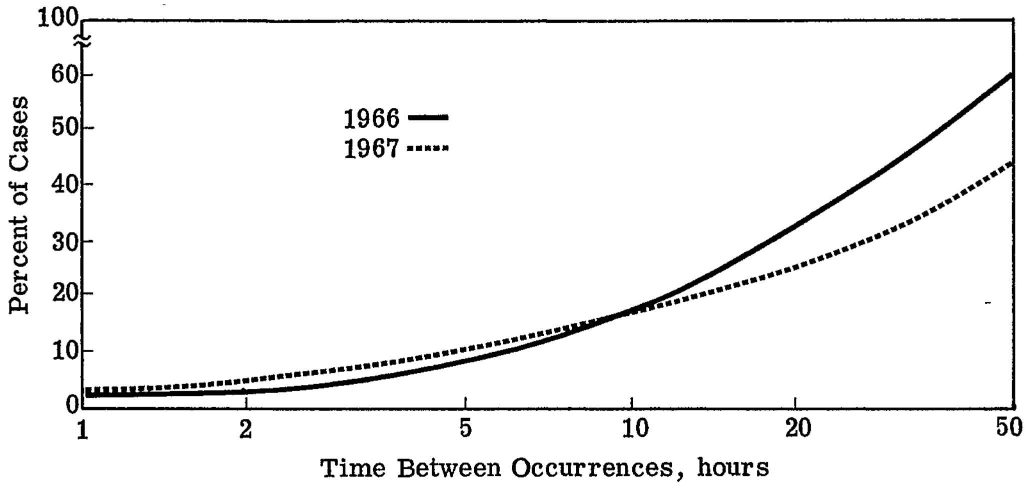


FIGURE 6. CUMULATIVE DISTRIBUTION FOR TIME BETWEEN CARDIAC ARREST EMERGENCIES

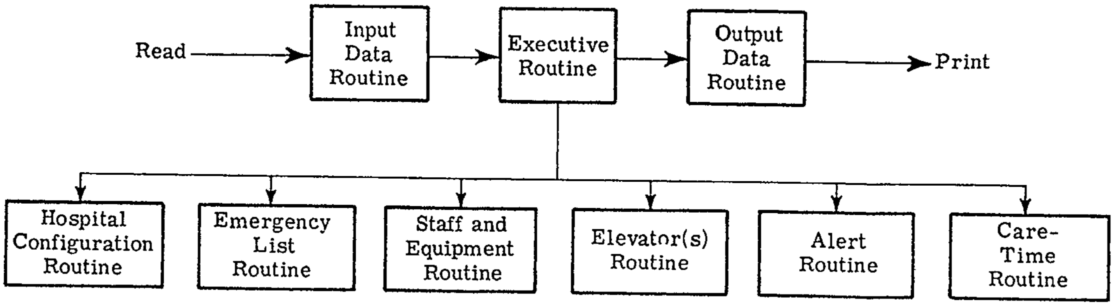


FIGURE 7. CURRENT AND HECS OVERALL SIMULATION FLOW DIAGRAM

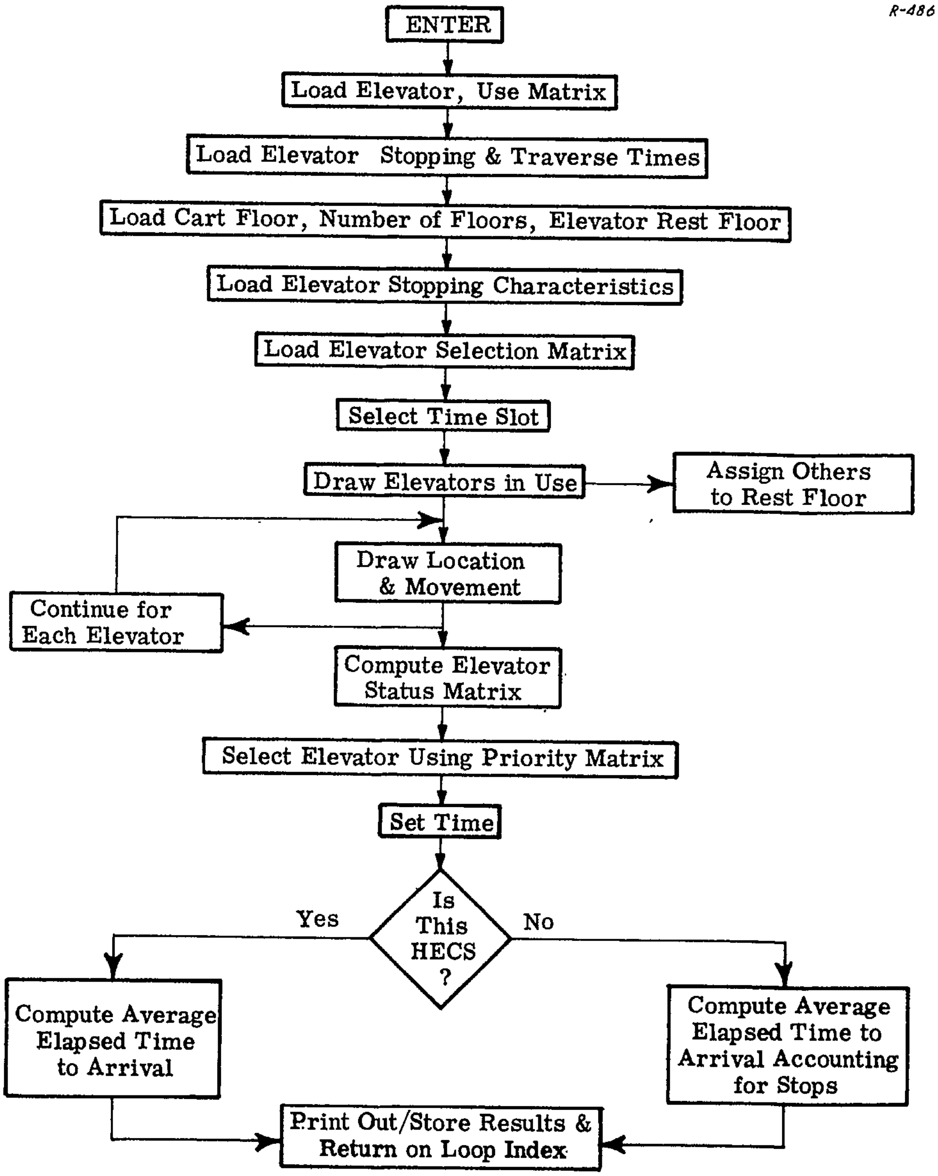


FIGURE 8. ELEVATOR SIMULATION ROUTINE LOGIC

TABLE 2

ALERT DELAY BUDGET

Current System		HECS	
Dial Operator	10 sec	Dial HECS	10 sec
Operator Response		Record Data	10 sec
Exponential Distribution		Public Address System Page	5 sec
11 pm - 7 am	k = 5 sec	MD's Hear Page	5 sec
7 am - 3 pm	k = 15 sec	Cart Nurse Responds	
3 pm - 11 pm	k = 10 sec	Exponential Distribution	
Operator Records Data	10 sec		k = 10 sec
Operator Calls MD's on Public Address	15 sec		
Operator Dial Cart	10 sec		
Cart Nurse Responds			
Exponential Distribution			
	k = 10 sec		

TABLE 3

TRAVEL TIME BETWEEN BUILDINGS IN MINUTES

Buildings	X	Y	Z	W
X	0	1.5	0.75	0.5
Y	1.5	0	0.75	2.0
Z	0.75	0.75	0	1.25
W	0.5	2.0	1.25	0

CURRENT HOSPITAL EMERGENCY OPERATIONS

229 CARDIOPULMONARY ARRESTS

RESPONSE TIME IN MINUTES

	FRACTION OF CASES						
	.95	.9	.7	.5	.3	.1	.05
MD1	2.16	2.35	2.99	4.02	4.58	5.76	6.21
MD2	1.16	1.32	3.95	4.42	4.86	5.88	6.34
CART	1.35	1.48	2.82	4.00	4.64	5.87	6.33
TOTAL CARE	3.83	3.98	4.48	4.92	5.63	6.61	7.44
PARTIAL CARE	2.35	2.48	3.32	4.18	4.67	5.98	6.42
ALERT DELAY							
MD1	0.59	0.60	0.65	0.69	0.76	1.04	1.23
MD2	0.59	0.60	0.65	0.69	0.76	1.04	1.23
CART	0.81	0.85	0.92	1.03	1.16	1.48	1.65
CORRIDOR DELAY							
MD1	0.86	0.94	1.04	1.48	1.68	2.43	2.51
MD2	0.47	0.58	1.67	1.75	1.83	2.28	2.30
CART	0.45	0.47	0.94	1.48	1.70	2.44	2.52
ELEVATOR DELAY							
MD1	0.46	0.63	1.11	1.67	2.09	2.78	3.57
MD2	0.0	0.0	1.37	1.70	2.15	3.11	3.69
CART	0.0	0.0	0.79	1.44	1.78	2.53	3.20

FIGURE 9. CURRENT OPERATIONS SIMULATION RESULTS AND DELAY COMPONENTS

HECS EMERGENCY OPERATIONS

229 CARDIOPULMONARY ARRESTS

RESPONSE TIME IN MINUTES

	FRACTION OF CASES						
	.95	.9	.7	.5	.3	.1	.05
MD1	2.00	2.12	2.44	3.57	3.87	4.76	5.07
MD2	1.01	1.08	3.52	3.83	4.04	4.32	4.47
CART	0.95	1.02	1.88	3.08	3.41	4.33	4.67
TOTAL CARE	3.48	3.58	3.86	4.02	4.22	4.88	5.16
PARTIAL CARE	2.08	2.15	2.44	3.37	3.69	4.33	4.67
ALERT DELAY							
MD1	0.50	0.50	0.50	0.50	0.50	0.50	0.50
MD2	0.50	0.50	0.50	0.50	0.50	0.50	0.50
CART	0.43	0.44	0.49	0.55	0.66	0.82	0.87
CORRIDOR DELAY							
MD1	0.91	0.94	1.05	1.47	1.70	2.45	2.50
MD2	0.51	0.58	1.67	1.75	1.84	2.25	2.29
CART	0.44	0.48	0.95	1.46	1.70	2.42	2.49
ELEVATOR DELAY							
MD1	0.47	0.64	0.88	1.48	1.71	2.03	2.20
MD2	0.0	0.0	1.19	1.40	1.60	1.92	2.04
CART	0.0	0.0	0.43	0.96	1.14	1.44	1.64

FIGURE 10. HECS OPERATIONS SIMULATION RESULTS AND DELAY COMPONENTS

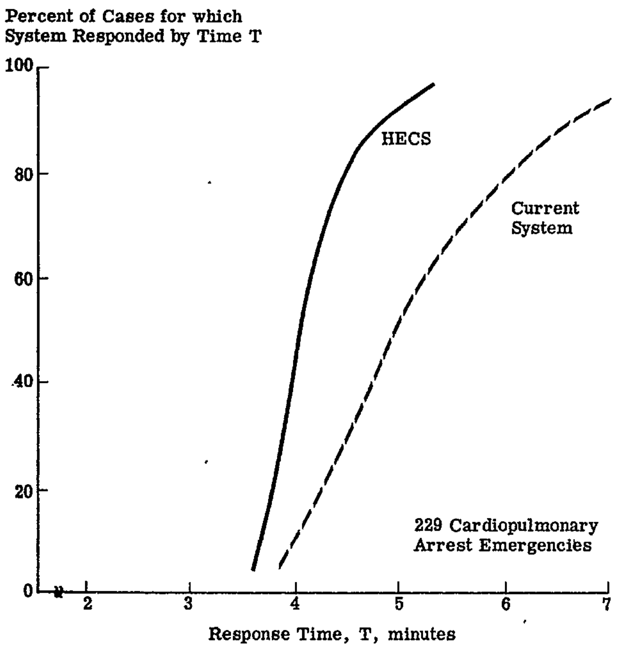


FIGURE 11. "TOTAL CARE" SIMULATION RESULTS

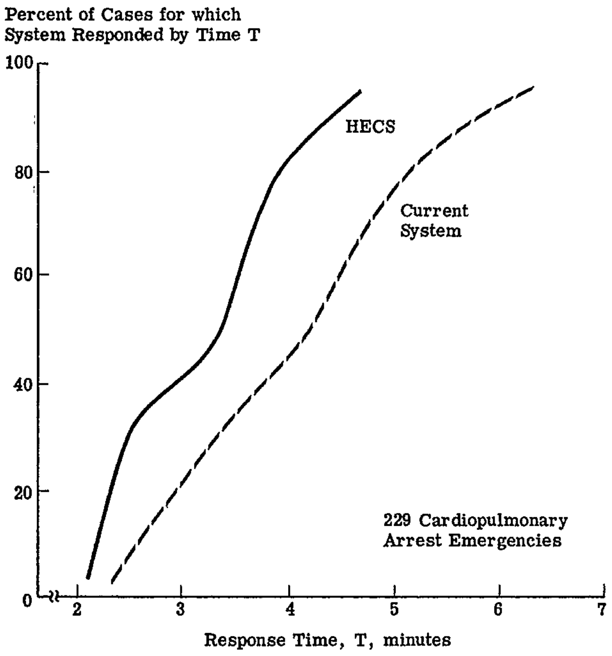
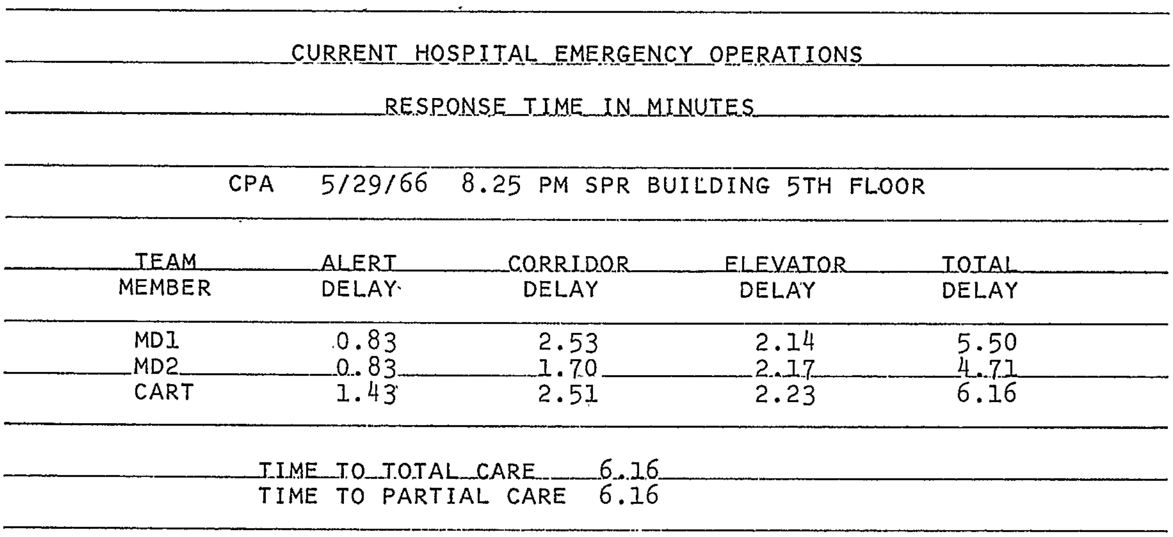


FIGURE 12. "PARTIAL CARE" SIMULATION RESULTS



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                CURRENT HOSPITAL EMERGENCY OPERATIONS

                      RESPONSE TIME IN MINUTES

        CPA    5/29/66   8.25 PM SPR BUILDING 5TH FLOOR

      TEAM        ALERT       CORRIDOR       ELEVATOR       TOTAL
     MEMBER       DELAY        DELAY          DELAY         DELAY

      MD1          0.83         2.53           2.14          5.50
      MD2          0.83         1.70           2.17          4.71
      CART         1.43         2.51           2.23          6.16

             TIME TO TOTAL CARE     6.16
             TIME TO PARTIAL CARE   6.16
```

FIGURE 13. INDIVIDUAL CASE REPORT

TABLE 4

INTERDECILE RANGE OF
SIMULATION RESULTS IN MINUTES

Care Case	Current System	HECS
Partial	3.5	2.2
Total	1.6	1.3

TABLE 5

PERCENT OF CASES FOR WHICH
SYSTEM RESPONDED IN A GIVEN TIME

System Case	Three Minutes	Four Minutes
Current System	21	47
HECS	41	82

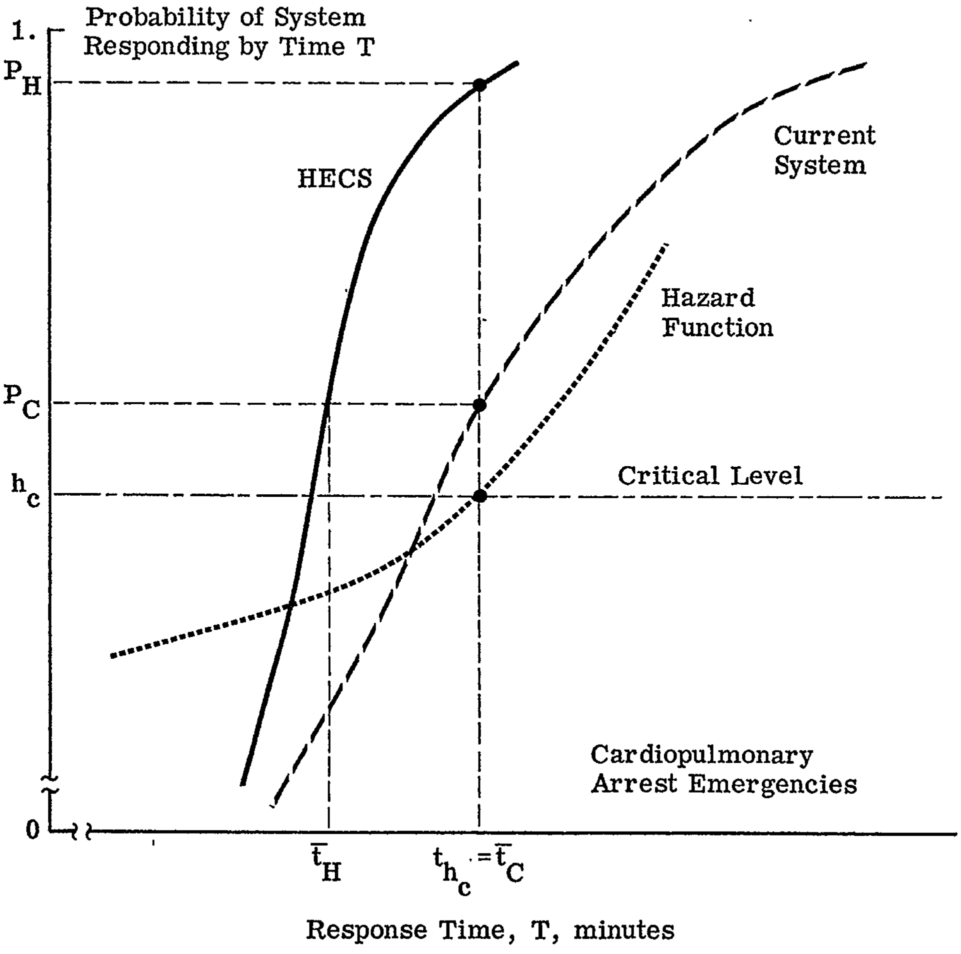

FIGURE 14. EFFECTIVENESS OF RESPONSE SYSTEMS

BIOGRAPHY

Stephen A. Levine, Head of the Public Systems Engineering and Management Sciences Group at The Analytic Sciences Corporation (TASC), has participated in and directed numerous analytic studies incorporating various aspects of system modeling, analysis, design, simulation, optimization and evaluation. He has over six years of experience in solving complex problems in research, engineering and management for government agencies, public institutions, and private industry.

Mr. Levine received the B.S., Cum Laude, in Applied Mathematics at the Polytechnic Institute of Brooklyn in 1962, the M.S. at the Massachusetts Institute of Technology in 1963, and he expects to complete the M.B.A. requirements at Boston College in 1970. He has received commendation from the United States Air Force for his work in systems analysis and has published several papers in technical journals. Mr. Levine is a member of Sigma Gamma Tau, Operations Research Society of America, and The Institute of Management Sciences.