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SIMULATION MODELING OF PREHOSPITAL TRAUMA CARE

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ABSTRACT

Prehospital emergency care systems are complex and do not respond predictably to changes in management. A combined discrete-continuous simulation model focusing on trauma care was designed and implemented in SIMSCRIPT II.5 to allow prediction of the effect of policy changes on system performance and patient survival.

1 INTRODUCTION

Prehospital care of the sick and injured has developed into a complex system in the last 30 years. Much of this development has been "bottom-up," driven by technological factors and the availability principle (any available tool will eventually be used). This has led to considerable debate in the medical community over the appropriate role of various clinical protocols routinely employed in many localities. Furthermore, as resource constraints and other external factors have stressed the system, the need for a systematic overview has become apparent. This project developed a simulation model of a prehospital trauma care system to provide a method by which the effect of modifications to the system can be estimated.

Simulation has been previously used as an aid in planning and organizing such systems. Most of these simulations have concentrated on static aspects of the system, such as the number and location of responders (Fitzsimmons *et al* 1982, Uyeno and Seeburg 1984), improvements in response or transport time, *etc* (Valenzuela *et al* 1990). This project focuses more on clinical issues that are frequently modified dynamically by changing clinical and administrative policies.

2 SPECIFICATION

The system under consideration is that portion of the prehospital emergency medical care system (EMS) which deals with injury in the seven county service area of northeast Florida and southeast Georgia. The EMS system is obviously affected by non-traumatic illness as well, so the model must include some representation of their effects, but they will not be at the focus of the model. The specification describes the system's elements and their behavior, and the goals for the model.

2.1 System Elements

The system can be decomposed into five fundamental elements: patients, vehicles, receiving facilities, injuring events, and a transportation network over which vehicles move patients from sites of injury to or between receiving facilities.

Patients suffer injuries because of injuring events or accidents. The appearance of patients in the system is not independent, since an incident may produce several patients. In addition, injuries occur in the two broad, nonexclusive categories of blunt and penetrating. Within these categories, patterns of correlated injuries exist; for example, brain injury is typically isolated in penetrating trauma, but often associated with chest and abdominal injuries in blunt. Injuries differ in severity, and result in a physiological process that can be followed over time and used to determine survival.

Vehicles in the system are helicopter and ground ambulances, and private conveyances. Helicopter ambulances are typically few and therefore subject to more stringent dispatching criteria than ground ambulances. Ground ambulances and private conveyance are constrained to use the transportation network; helicopter ambulances generally travel faster and by line of sight, but are constrained by weather conditions and the need for a safe landing zone. Ambulance personnel may perform several therapeutic interventions before transporting the patient to a receiving facility, while private transportation provides no emergency care. In addition, ambulances can be directed to (and away from) different hospitals, and provide some advance notice of a patient's arrival, but private conveyances do neither.

Receiving facilities in the system are hospitals and other acute care facilities such as clinics or physicians' offices. Hospitals may be classified into Level 1, 2, or 3 trauma centers as defined by Florida statute. Or, they may choose not to participate in the trauma center system; their actual capabilities typically do not change by virtue of this decision. Receiving facilities will perform initial resuscitation and evaluation of incoming patients, and then transfer them out of the system to definitive care.

Injury incidents are independently distributed over time and space. Each event may produce one or more patients, although it need not produce any. Injury events produce either blunt or penetrating injury in their patients, and typically not both.

The transportation network consists of existing major roads, highways and bridges. A patient's transport time by ground conveyance depends on the available path through the transportation network and the time of day. Geographic barriers such as the St. John's River and other waterways are reflected in the transportation network. Because ambulances are most commonly directly managed by county governments, political boundaries also may affect transportation decisions. For example, in patients with minor injuries, the target receiving facility may be chosen such that the path to it does not involve crossing a county or state line; these considerations are dropped in the face of severe injury.

2.2 System Behavior

The system's behavior consists of a temporal sequence of discrete events in the system running concurrently and interacting with a continuous pattern of physiological changes in injured patients. The sequence begins with an injury-producing episode that generates one or more patients at a particular location and time with a given pattern and severity of injuries. The prehospital system is activated and an ambulance dispatched to the location, typically on a proximity basis. The time from injury to arrival on scene is termed *activation time*. Once on scene, EMS personnel may have to locate (Campbell 1992, Campbell 1993) and/or extricate patients, and may provide some therapeutic services such as intravenous fluid administration or endotracheal intubation. The time from arrival on scene until departure for a hospital is defined as the *scene time*. The patient is then transported to a receiving facility in *transport time*. The means of choosing a receiving facility (*eg*, nearest hospital, nearest hospital of a given level) is a source of recurring controversy and will be examined in the simulation. The receiving facility will perform initial resuscitation and evaluation and will then deliver the patient to definitive care (*eg*, the operating room, hospital admission, *etc*) after *resuscitation time* and some additional waiting time, which may be zero. Definitive care is considered outside the system. Occasionally, the receiving facility may transfer the patient to another facility, repeating the transport and resuscitation stages of the cycle.

During this process, the patient's physiological state will change depending on the injuries and therapy received. Some patients will die before being delivered to definitive care; for those who do not, their probability of survival will be estimated from their injuries and their physiological state at the time of exit from the system (Wears and Winton 1990, Champion *et al* 1991). Injuries can be categorized into three large groups based on their major physiologic effects: those producing blood loss, those interfering with respiratory exchange, and those affecting the central nervous system. In each of these categories, the physiologic state deteriorates over time without intervention. Indirect evidence of the severity of injury in these categories is combined into a "trauma score" (Champion *et al* 1984, Champion *et al* 1990, Champion *et al* 1991) which is used by EMS personnel to make therapeutic and transportation decisions.

2.3 Goals

Any simulation model should be constructed to answer specific questions, rather than just show that a model can be constructed. This model was designed to estimate the effects of changes in:

a. Triage criteria that determine the center to which a patient should be routed;
b. Criteria for helicopter transportation vs ground transportation.
c. Divert policy (the circumstances and length of time during which a hospital may divert incoming cases to another facility).

These effects will be measured from two perspectives: from the point of view of the system (numbers of patients received, percent utilization, *etc*) and from the point of view of the patient (length of time until definitive care, change in survival probability). Secondary goals include the ability to examine additional questions about the system as they arise, and the ability to apply the model to new EMS systems in other areas without reprogramming or recompilation.

3 DESIGN AND IMPLEMENTATION

General design issues for this project are those common to all simulation models: selection of a simulation environment and the appropriate level of detail, verification of the implementation, validation of model, and the design and analysis of appropriate experiments. The realization of the model in SIMSCRIPT will be provided on request.

3.1 Simulation Environment

The model was implemented in SIMSCRIPT II.5 (CACI Products, La Jolla, CA) for several reasons. SIMSCRIPT is available on many computer systems and has wide general acceptance as a simulation language, simplifying the potential portability of the model. The EMS model proper lends itself easily to discrete simulation, while the physiologic model is more naturally thought of as continuous; SIMSCRIPT provides support for simultaneous continuous and discrete simulation, thus helping to model the interaction between these two components. And finally, local expertise and experience with SIMSCRIPT was available.

3.2 Data Structures

Two general principles were used in representing entities in the model. First, entities having a potential lifespan in the model greater than a typical run length were represented as SIMSCRIPT permanent entities, while entities that potentially might "come and go" during a run were represented as SIMSCRIPT temporary entities. Second, no entity should have greater knowledge about itself or about conditions in the system than would its real-world analog. Application of these principles to the model entities described in Section 2.1 produced the following set of data structures: nodes, paths (a series of arcs connecting two nodes), hospitals, and ambulances were represented by permanent entities; arcs, dispatch lists, ambulance runs, accidents, patients and external events were represented by temporary entities or processes.

A programming construct called a "monitor" was used to handle interprocess communications. A natural monitor, the dispatcher, exists in the real-world system, so this approach meshed nicely with the target model. Interestingly, the monitor function was more easily provided as a procedure, rather than as a SIMSCRIPT entity. Thus, the dispatcher is the only major real world entity having only an implicit representation in the model. Although not specifically implemented as such, entities such as ambulances and patients can be viewed as finite state automata, with the dispatcher functioning to oversee state transitions.

3.3 Statistical Issues

The common random numbers technique was used to reduce variance between policy alternatives. Special care was taken to ensure synchronization of the random number streams. Although the system under study does not possess well-defined starting and ending times, it does empty out from time to time. Therefore, no warm-up period to eliminate the effect of start-up transients was used. Instead, the model was started empty and idle, and the regenerative method used to determine run lengths; *ie*, a run is ended when the system returns to the empty and idle state.

The primary goal of the model is effect estimation, not hypothesis testing. Statistical testing of the differences between model outputs under differing policies is complicated by the use of the regenerative method, since it cannot be guaranteed that parallel runs will always be directly comparable, even though every random component for each patient is guaranteed to be comparable. For example, individual runs might not necessarily have the same numbers of patients; in general, parallel runs will diverge and reconverge at unpredictable points. Naive direct comparisons of alternatives as if they were independent will overestimate the variance of the difference in effect. To properly compare the alternatives, summary measures must be calculated at a point where the model has reconverged under each alternative.

Data for the model were obtained directly from Fire/Rescue records whenever possible. The distributional form of the input random variables was chosen after consideration of both theoretical and practical issues. For example, for those distributions known to be bounded, beta distributions were chosen since they were also bounded, and were then scaled and fit using moment matching or maximum likelihood methods. Similarly, if a distribution was known to be skewed to the right, or nonnegative, candidate distributions were restricted to those having the appropriate general characteristics. For all distributions for which empirical data was available, the choice among candidate distributions was made by visually assessing probability and quantile plots (Law and Kelton, 1991), after matching the first two moments (mean and variance) to the empirical data.

Twenty-six random variables were used in the model. Since SIMSCRIPT by default provides only ten random number streams, each 100,000 variates long, its standard random number generator was modified to support 30 random number streams, each 1,000,000 variates long. In addition, provision has been made to use other random number generators for any or all of the random variables in the model.

3.4 Patterns of Injury

The spatial pattern of injury was assumed to be roughly proportional to population density. This has been shown to be the case in at least one major city (Pepe, Curka, Zachariah, *et al*, 1992). Pepe *et al* also showed that the distribution of types of accidents (*eg*, assault, auto accident, gun-shot wound, *etc*) was independent of time and space; this assumption was incorporated into the model.

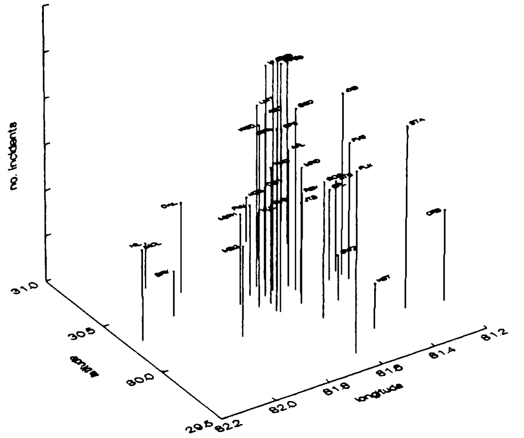

Figure 1: Spatial distribution of trauma incidents in the study area

The temporal pattern of injury was modeled by a non-stationary batch Poisson process (Çinlar 1975). Raw data kindly provided by Zachariah (personal communication) was used to estimate the diurnal pattern of injury occurrence. This was combined with weekly variation (Baker 1992) to produce the weekly cycle of injury incidence used in the model. The spatial distribution of incidents is illustrated in Figure 1, Figure 1, and roughly corresponds to population density in the target area.

3.5 Transportation Network

The geographic area of interest was represented at a higher level than blocks or map coordinates by modeling the area as a digraph. Nodes in the graph represent certain critical areas, such as: neighborhoods or fire-rescue service areas from which requests for care arise; choke points -- areas such as bridges which transporters must traverse en route to their destination; and receivers, typically hospitals categorized according to Florida's trauma statute. Arcs in the digraph represent logical routes between nodes, not necessarily physical roads. Arcs were assigned weights representing travel time across them; these weights may vary with time of day. While some information on average transport times is available from the Fire-Rescue system, information about the distribution of transport times is not. However, Campbell (Campbell92, Campbell 1993) has published detailed summary results of a variety of prehospital time intervals, and kindly agreed to provide his raw data for use in the project (personal communication). Therefore, distributions were fit to Campbell's data using quantile and probability plots, or occasionally using the method of moments.

Since there are extensive and highly functional mutual assistance agreements among the political jurisdictions in the study area, political boundaries have not been explicitly represented in this implementation. It would be possible, if desired, to represent political boundaries by placing an empirical penalty function on the pertinent arcs; such a penalty function would be greater for minor injuries and zero for major injuries.

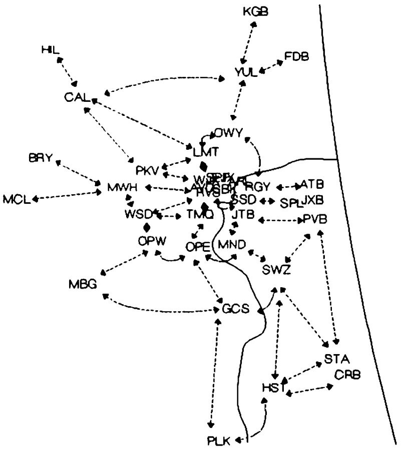

Figure 2: Transportation Network as a Digraph

Only a finite area was simulated, but resources located near the boundary of the simulated area might be called to service events occurring beyond the boundary; similarly, injuries occurring within the boundary might be managed at hospitals outside the boundary. In the system under consideration, the boundaries tend to fall at "watersheds" where events are rare, and very little boundary crossing occurs. For example, it is common for ambulances in St. John's county to respond to calls in or transport patients into Duval county; it is uncommon that they do so with respect to Flagler county, because of population densities and pre-existing referral patterns. Therefore, these "edge effects" were neglected save for judiciously choosing the boundaries of the simulated area to keep them to a minimum. A simplified version of the digraph modeling the geographic area is shown in Figure 2.

Average node to node times within the transportation network routes were precomputed and stored prior to a simulation run. These times were used to generate ambulance call lists for each node, and hospital destination lists for each node, and the basis of shortest expected travel time. The call and dispatch lists were saved in a file that can be edited to reflect special circumstances. Helicopter ambulances are assumed to be callable to any locations, and to take turns in responding to calls. The choice of helicopter *vs* ground ambulance is based on Trauma Score and distance by current policy, and will be the subject of experimentation.

3.6 Physiologic Model

Injuries occur in identifiable patterns that a model should represent to achieve face validity. Ideally this requires generation of categorical variables having a given correlation. While many simulation models have assumed independence of variables, apparently successfully, there are several instances (Law and Kelton 1991) in which it has been shown that the failure to model correlation between variables substantially affected the results. Although Devroye (Devroye86) and Johnson (Johnson 1987) have offered several plausible approaches toward the general problem of generating correlated random variates, neither has specifically addressed this problem. Unfortunately, the covariance structure of within-patient injury patterns has yet to be described quantitatively. Therefore, it was necessarily assumed that blunt and penetrating injuries had the same distribution of injury severity. Injury severity was modeled by assigning a values drawn from a scaled beta distribution fit to data from MacKenzie (MacKenzie *et al* 1986) to patients representing their Injury Severity Score (ISS), (Baker *et al* 1974), and then partitioning the total ISS among the three major categories of physiologic derangement as suggested by Baxt and MacKenzie (Baxt *et al* 1987, MacKenzie *et al* 1986), and finally mapping those components to either direct physiologic variables (*eg*, blood pressure) or to components of the Revised Trauma Score (RTS: see below), (Champion *et al* 1991). The RTS values thus computed were validated by comparing their distribution to the distribution of RTS reported previously (Champion *et al* 1984, Champion *et al* 1986, and Morris *et al* 1986) with good agreement.

Each patient was represented as a distinct entity within the model, as were resources such as ambulances, helicopters, and hospitals. A limited set of physiologic variables was modeled for each patient, since detailed physiological modeling (Mazzoni 1988) is computationally intensive. The model of hemorrhage developed Lewis (Lewis 1986) and modified by Wears and Winton (Wears and Winton 1990) was adapted for use in this project by extending it to accommodate respiratory exchange. Direct central nervous system injury seems to be a distinct problem (Baxt 1987) that is synergistic with both hemorrhage and respiratory injury. It was therefore modeled as a "black box" process, whose main effect is to cause a downward adjustment in the probability of survival.

The three components of the physiologic model were used to compute the Revised Trauma Score (RTS), (Champion *et al* 1984, Champion *et al* 1991), which, together with the ISS has achieved general acceptance in predicting survival. The RTS assigns each component of the physiologic model a value on a 0 to 4 scale. These scores may then be simply summed to form a 0 to 12 scale, but a weighted sum (Champion *et al* 1991) with a maximum total of 7.804 is thought to provide better prediction. A mapping between the hemorrhage component and these scores has already been developed (Wears and Wintion 1990).

3.7 Output Measures

Certain critical variables were used as the basis of comparison between policy alternatives. These included the dynamic proportion of utilization of trauma centers at each level. Since trauma centers typically must maintain excess capacity, an alternative measure of utilization, the proportion of time the center is not at or over capacity, (*ie*, the center could handle an additional patient) was also tracked. Other important outcome measures include the total time in the system, the mortality in each phase prior to definitive care, and the probability of survival following definitive care.

4 Verification and Validation

Major components of the implementation were verified against predictable model elements wherever possible. This was done by independent testing of "stub" routines where practical, and by inspection of the simulation trace or outputs elsewhere. Separate verification runs checking aspects of the model's logic have been performed and compared to specific test cases derived from available Trauma Registry data. Many of these verification runs were initially performed at the module level so that the desired (true) behavior of the model can be more easily predicted. An activity trace is produced by the model to aid in verification and validation.

The model was validated by checking its output against aggregate data on injury types, patterns of transportation and survival using published data and the trauma registry maintained by University Medical Center in Jacksonville. Unfortunately, detailed data on the overall operation of the prehospital care system is not maintained; a modified Turing test may help in further model validation. The current level of validation of the model is not considered sufficiently definitive for the model to be used in establishing policy. Further validation will require formalized collection of data from the system for comparison to model output.

4.1 Random Variate Generators

Two new random number generators were coded and verified; the non-stationary Poisson distribution routine *nsp.f*, and *mygamma.f*, a replacement for SIMSCRIPT's gamma variate generator, which can be shown to be erroneous for large values of the shape parameter. (The beta variate generator also had to be modified, because it uses gamma variates). Çinlar's method (Çinlar 1975) of generating the interarrival times for a non-stationary Poisson arrival process was implemented in the function *nsp.f*. Goodness of fit testing on a variety of sample data sets showed no evidence of poor fit, giving grounds for acceptance of the nsp.f function.

The gamma variate generator was implemented from two published algorithms (Bratley *et al* 1987). For shape parameter greater than one, Tadikamalla's method was used, and for order one or less, Ahrens' method. Verification examples were produced over a wide range of arguments including those known to return invalid results for the SIMSCRIPT generator.

4.2 Static and Dynamic Analysis

The realization of all random variables in the implementation was checked to confirm that they agreed with their specified parameters and distributions. For example, the distribution of observed ISS scores in the model compared reasonably well to that described by Baker (Baker *et al* 1992), which it was designed to match. Similarly, the proportion of blunt to penetrating injury, the spatial distribution of injuries, the number of victims per accident, and other elements were confirmed to approximately match their real world counterparts.

The dynamic behavior of the implementation was verified to be compatible with the model by careful inspection of the trace output and temporal outputs such as blood pressure. Special attention was paid to dispatching rules, such as alternating assignments between helicopter ambulances, or between two ambulances based in the same node. It was possible to confirm from the trace dispatched ambulances that were recalled had indeed not reached the scene. It was also confirmed that ambulances treated patients in order of severity as manifested by the current value of the RTS. And finally, the trace confirmed that no ambulance was dispatched to the "wrong" node or to the "wrong" hospital, and that no ambulance traveled to a hospital without carrying a patient. This method of verification can never absolutely confirm the reliability of the system, but it does serve to increase confidence that the implementation behaves according to the model's specifications.

Table 1: Outcomes Estimated by the Model Compared with Observed and Literature

item	model	observed	other
mean daily:			
amb runs	41.734	44.0	n/a
helo runs	5.07	5.0	n/a
probability of death:			
on scene	0.018	0.01	n/a
before definitive care	0.128	0.05	0.085
mean systolic blood pressure at definitive care	93.8	100.0	95.4
mean transport time (minutes)	22.1	20.0	n/a

Rigorous validation of a system such as this is extremely difficult, primarily because of the inadequacy of existing data sets useful for confirming model performance (McCoy *et al* 1992). However, it was possible to compare measures of the model's performance to locally available data elements, to establish at least order of magnitude validity. The following items had sufficient data available to allow such comparisons: number of ambulance runs, number of helicopter runs, proportion of deaths prior to definitive care, *etc.* The model's predictions for these variables are compared with convenience sample estimates from Jacksonville Fire Rescue and published data in Table 1. The distribution of transit times was compared with that derived from Campbell's data. Mean transit times were different, reflecting differing geography, but quantile plots of the two data sets revealed that they have approximately the same distribution, differing only by a scaling factor.

5 Demonstrative Experiments

The utility of the model was demonstrated by experiments testing the effects of changes in triage and helicopter dispatch policies.

5.1 Triage Policy

Three sets of runs were performed using a different cutoff point to determine when a patient should be triaged directly to a Level 1 trauma center, bypassing other (possibly closer) hospitals. Current standard operating procedure calls for all patients with an RTS less than or equal 10-11 on the 0-12 RTS scale (corresponding to a score of approximately 90% of the weighted maximum of 7.8408) to be transported directly to a Level 1 center, even if lower level centers might be closer. This baseline case and two alternate cases were simulated. The minimum run length was set to 24 hours, and a total of 28 runs (approximately one month) were performed. The following outputs were used as measures of system performance under each scenario: trauma center utilization, red time, and reserve; proportion of accidents pended (*ie*, no ambulance immediately available), mean waiting time until an ambulance is dispatched among pended accidents; helicopter utilization; mean probability of death prior to receiving definitive care; unmet need (patients who met helicopter dispatch criteria but for whom a helicopter was unavailable); and total waiting time until EMS arrival. The classical approach (Law and Kelton 1991) was used to calculate point and interval estimates from the results of the 28 regeneration cycles.

The results for the baseline case and two alternatives (triage cutoffs of 80% and 95% of maximum) are summarized in Table 2. Compared to the baseline case, the main effects of liberalizing the triage cutoff are an increase in helicopter utilization, and a decrease in the length of time that a pended accident must wait to have an ambulance assigned to it. In addition, some variables such as unmet need and the probabilty that no ambulance is available when the an accident requests one were noted to behave unpredictably.

The three alternatives at six points in the simulation; results at the two convergence points spanning at least a full week cycle are shown in Table 3. After adjusting for multiple comparisons, the results show that helicopter utilization is significantly different under the 80% and 95% triage cutoffs ($P = .013$, paired t test); the 95% confidence interval on the difference in utilization between these two alternatives is .036 ± .0014, or about a 33% increase. Although the mean difference in waiting time for pended accidents is large between the 80% and 95% policies (9.2 minutes), the difference is not statistically significant. This could be due to inadequate power since only two point estimates were obtained; further runs would be required to improve the precision of the estimate to see if a true effect on waiting time should be expected.

Table 2: System Performance over 30.928 Days under Different Triage Criteria

RTS cutoff (% of max)	80	90	95
trauma center			
daily pts	21.9	22.6	23.0
utilization	.288	.301	.304
red	.000	.000	.001
reserve	.9998	.99996	.9997
probability			
no amb	.042	.053	.042
wait (min)	31.4	24.8	22.0
helicopter			
utilization	.112	.135	.148
unmet need	.266	.340	.322
probability			
death*	.120	.122	.123
activation time (min)	21.4	21.6	21.1

*prior to definitive care

Table 3: Convergence Points Including at Least a Seven Day Cycle

	helo utilization			waiting time		
RTS cutoff (% of max)	80	90	95	80	90	95
convergence time (days)						
13.919	.128	.139	.163	34.2	21.0	22.7
30.928	.100	.133	.136	28.0	28.3	21.2

5.2 Helicopter Dispatch Policy

Currently, helicopter ambulances are dispatched for patients needing a level 1 center whose transport time is over 19 minutes, and patients needing a level 2 center whose transport time is over 39 minutes. The effects of reducing these times by about 50% (to 10 and 20 minutes, respectively) are shown in Table 4; the triage cutoff was kept at 90% of maximum, so these results should be compared to the center column in Table 2. It appears that the effect of liberalizing time and distance transport criteria on helicopter use is much greater than that of liberalizing the triage cutpoint, yet the latter has received considerably more attention.

Table 4: System Performance (Mean ± 95% CI) under Alternate Helicopter Dispatch Criteria

trauma center		
utilization	0.298	± 0.037
red	0.000	
reserve	0.9999	± 0.0001
pr acc pended	0.042	± 0.019
wait (min)	24.4	± 8.86
helicopter		
utilization	0.160	± 0.021
unmet need	0.293	± 0.037
pr death*	0.112	± 0.020
time til arrival	22.2	± 1.74

*prior to definitive care

6 Conclusions

It is interesting to note that the trauma triage cutoff, which has been the subject of vehement debate at times, had little effect on the overall load on the system, while a factor that has received little attention, the retriaging of less severely injured patients to a higher level of care if such a center is reasonably "close" had a much greater impact. This leads to the conclusion that the common knowledge of domain experts may not always be helpful in predicting the response of a complex system to change, and that computer models of such systems may enhance the decision makers accuracy and reliability by adding insight into the possible responses of the system to variables that were not previously thought important.

Concern for the validity of current disaster planning and a demonstration of the potential of this model has led to community-wide interest in using a more fully validated version of the model to assist in planning for several events of importance in northeast Florida. The particular areas of interest are:

a. Modifying the current triage policy to take all patients to the nearest hospital, which would perform rapid stabilization and transfer to a Level 1 center for critically injured patients.

a. Loss of a hospital and subsequent evacuation of its patients to other facilities.

b. Loss of a major "choke point" such as a bridge for hours to days.

c. Widespread flooding of low areas eliminating multiple transportation routes and isolating some hospitals and nodes.

d. An area-wide disaster such as a hurricane, which might combine all of the preceding elements.

e. Modification of the physiologic model to use a more detailed physiologic score such as ASCOT (Champion *et al* 1990), and to estimate the covariance structure of injuries from the American College of Surgeons National Trauma Registry Data (TRACS).

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