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Analysis of the suitability of the trauma center location configuration in the state of Arkansas

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Abstract

With the Arkansas trauma system framework having been so recently enacted, analysis of the suitability of the trauma center location configuration has yet to be explored. A variety of optimization models were created that placed an emphasis on different objectives. These results were then used to evaluate the effectiveness of Arkansas's current system in relation to the optimal system generated by the mathematical models. Initial results indicated the areas that are not covered by the current trauma system. In addition, further research revealed the optimal number of trauma centers that could service the same population currently being served. Assessing the suitability of the current system offers the possibility of exploring an alternative allocation of resources to improve the location configuration and better serve the health services needs of the people of Arkansas.

Introduction

Trauma, which encompasses accidents or unintentional injuries, is the primary cause of death for people ages 1-44 (*National Vital Statistics* 2012). As a result, the need for a coordinated trauma system is essential for each geographical area throughout the country. A trauma system is an organized, coordinated effort in a defined geographic area that delivers the full range of care to all injured patients and is integrated with the local medical and public health systems (*California* 2006).

With the signing of Act 393 in 2009, the state of Arkansas is the last in the nation to develop a statewide trauma system (Moritz 2012).

An integral part of the success of all trauma systems is the optimal location of appropriate trauma centers. Each trauma center is designated a certain level, which corresponds to the degree of care that center can offer (Moritz 2012). Emergency rooms treat minor injuries and illnesses, but trauma centers and their associated resources are required for all severe, life-threatening injuries. Emergency medicine defines the "golden hour" as the first 60 minutes after a major trauma (*Trauma* 2013). It is a common belief that a patient's chances of survival are at their peak if appropriate care is given within this critical time period. The golden hour can be succinctly defined by the 3R rule of Dr. Donald Trunkey, an academic trauma surgeon, "Getting the right patient to the right place at the right time" (*Trauma* 2013). A suitable trauma center location system is essential if each patient is to reach the "right place" at the "right time."

This research intends to explore existing quantitative criteria for trauma center location planning, and to use these criteria to evaluate the current state of the trauma system in Arkansas. To do this, a variety of optimization models will be created that place an emphasis on different objectives. These results will be used to evaluate the effectiveness of Arkansas's current system in relation to an optimal system generated by the mathematical models. For example, suppose a criterion in locating trauma centers is to locate facilities such that a patient located anywhere in the state can reach a trauma center within sixty minutes. First, we can examine the current trauma center locations in Arkansas and determine whether this criterion is met by the current system. Then, we can use an optimization model to determine the *best* places to locate trauma centers with respect to this criterion. This analysis can provide insight when making future changes to the current trauma system. For example, the analysis could reveal that a trauma center needs to be added in a specific region of the state. Or, it could reveal that it would be possible to meet the criterion with a fewer number of trauma centers, therefore fewer resources.

With the Arkansas trauma system framework having been so recently enacted, analysis of the suitability of the trauma center location configuration is pertinent. It has not yet been adequately evaluated. Arkansas's delay in creating this statewide trauma system until just recently requires that the system be implemented in a timely and optimal manner.

Literature Review

This research is aimed towards evaluating and analyzing the current state of the trauma system in Arkansas. Before explaining the trauma aspects necessary to a system, an understanding of the nature of locating these trauma centers is necessary. At its core, the creation of a trauma system is a strategic facility location problem. A trauma system can be represented by a static or dynamic formulation of a facility location problem with specific stochastic characteristics. Stochastic formulations attempt to capture the uncertainty in problem input parameters, like distance values. The literature on stochastic formulations is divided into two categories: that which considers the probability distribution of uncertain parameters, and that which captures the uncertainty through scenario planning

(Daskin et. al. 1998). A basic dynamic facility location problem with additional stochastic characteristics is an adequate representation of a trauma system allocation problem.

A significant amount of research has been done concerning the allocation of trauma care resources, specifically within individual states. Branas, MacKenzie, and ReVelle used statistical information from Maryland's statewide trauma system to develop the Trauma Resource Allocation Model for Ambulances and Hospitals (TRAMAH). It was concluded that this model allows trauma system planners to more accurately allocate their trauma care resources with respect to spatial restrictions and response times (Branas et. al. 2000).

In addition, the consideration of trauma service cost is influential in trauma center allocation decision-making. Tahari et. al. identified cost centers associated with trauma care and how to reduce them (Butz et. al. 1998). In general, cost analysis concerning trauma center allocation has not been thoroughly developed in terms of statewide trauma systems.

Research has also been done concerning the price of commitment in the creation of a Level 1 Trauma Center and the resulting outcomes. Rotondo et. al. (2009) determined monetary values for the commitment cost of implementing Level 1 trauma care within a hospital and the cost of saving a life, and the benefit in terms of number of lives saved. These values can effectively be used in financial planning and budget allocation for health care resources within the state (Bard et. al. 2009).

While the objective of this research is most similar to that done by Branas, MacKenzie, and ReVelle, there is a major difference in the resources being considered. This research will consider locating trauma centers of various levels, as opposed to the allocation of hospitals and ambulances. The existing state of the newly created statewide trauma system in Arkansas will be analyzed, providing decision makers with insights as to how best to improve its configuration.

Analysis of the Current Trauma System

The initial stages of this research sought to explore existing quantitative criteria for trauma center location planning, and use these criteria to evaluate the current state of the trauma system in Arkansas. Emergency medicine defines the "golden hour" as the first 60 minutes after a major trauma (*Trauma* 2013). It is a common belief in the medical field that a patient's chances of survival are at their peak if appropriate care is given within this time frame. As a result, this critical 60-minute period was chosen as the base criterion to evaluate the effectiveness of the current state of the Arkansas trauma system.

An evaluation of the current trauma system in Arkansas was conducted through analysis of the locations of included trauma centers, and their respective distances to the existing population. The distribution of the current population in Arkansas was modeled using a geocoding approach and the Census 2010 Zip Code Tabulation Areas (ZCTAs) from the U.S. Census Bureau. ZCTAs are a statistical entity developed by the U.S. Census Bureau for tabulating summary statistics. Essentially, ZCTAs are generalized area representations of the U.S. Postal Service Zip Code service areas ("Zip Code Tabulation Areas," 2013). Each ZCTA has a specific location and population associated with it, which makes it ideal for analyzing population coverage. The locations for these ZCTAs were obtained in the form of latitudes and longitudes. Location data for each of the 71 trauma centers within the Arkansas trauma system was also obtained in this format using a geocoding system.

Current Arkansas Trauma System Analysis	
% of Population Not Within 60 minutes of a Level I Trauma Center	64.8%
% of Population Not Within 60 minutes of a Level I or II Trauma Center	41.1%
% of Population Not Within 60 minutes of a Level I, II, or III Trauma Center	7.77%
% of Population Not Within 60 minutes of any Trauma Center	0.33%

Table 1: Current Arkansas Trauma System Analysis Results

The location data for each of the ZCTAs and trauma centers was organized into 596 destination matrices, with each matrix containing one ZCTA destination and the 71 potential trauma center destinations. Each of these matrices was evaluated using the Google Maps Distance Matrix API tool, which accepts a destination matrix and returns a distance matrix containing mileage and time value distances between the points based on existing roadways. After inputting each of these destination matrices into the Google Maps Distance Matrix API tool, Visual Basic code was written to parse the generated JSON results of these matrices. An excerpt of the parsed output from these matrices can be referenced in Figure 3 in the Appendices. This output was then analyzed to determine the effectiveness of the current system. This analysis was conducted by determining whether or not each ZCTA was “covered” by one of the 71 trauma centers; in other words, whether or not the population of each ZCTA could reach one of the 71 trauma centers within the critical 60-minute time frame. The results of this analysis can be seen in Table 1.

The initial conclusions that can be drawn from these results seem favorable, as only 0.334% of the population is not covered by a trauma center. However, upon further examination of the data, the fact that over 60% of the population is not within 60 minutes of a Level I trauma center emerges (Table 1). Nearly all of the population is able to reach a trauma center in under an hour, but the centers they reach may not be fully equipped to handle the trauma. Further analysis reveals that the Level 1 trauma center that is closest the majority of the ZCTAs is Arkansas Children's Hospital. While these ZCTAs are technically covered by a Level 1 trauma center, adults cannot be effectively treated at children's hospitals. As a result, the percentage of the population that is not able to reach a universal Level 1 trauma center is nearly 70% (Table 2).

Level I Trauma Center Attainability (excluding Arkansas Children's Hospital)	
# of ZCTA's Not Within 60 minutes of a Universal Level I Trauma Center	490
% of ZCTA's Not Within 60 minutes of a Universal Level I Trauma Center	82.21%
# of People Not Within 60 minutes of a Universal Level I Trauma Center	1,967,837
% of Population Not Within 60 minutes of a Universal Level I Trauma Center	67.354%

Table 2: Universal Level I Trauma Center Attainability

Optimization Model Results

The latter stages of this research dealt with the creation of an optimization model to determine the best placement of trauma centers within the state of Arkansas. The base strategic facility location model used was a maximal covering problem, which seeks to maximize the amount of demand covered within an acceptable service distance by locating a fixed number of facilities. In this case the amount of demand is the population, the service distance is the "golden hour" of trauma, and the facilities are the trauma centers. This basic model was adapted to meet the specific needs of this optimal location problem. The specific adaptation used can be viewed below:

<u>Sets</u>

I = indexed set of ZCTAs, i (demand nodes)

J = indexed set of Trauma Center locations, j (potential facility sites)

<u>Parameters</u>

h_i = population at ZCTA i

d_{ij} = travel time between ZCTA i and Trauma Center j

P = number of trauma centers to be located

<u>Variables</u>

$$X_j = \begin{cases} 1 & \text{if we locate a Trauma Center at Trauma Center location j} \\ 0 & \text{otherwise} \end{cases}$$

$$Z_{ij} = \begin{cases} 1 & \text{if ZCTA i is covered by Trauma Center location j} \\ 0 & \text{otherwise} \end{cases}$$

Objective

Maximize

$$\sum_{ij} h_i Z_{ij} - \frac{1}{M} d_{ij} Z_{ij} \quad (1)$$

Constraints

Subject to:

$$Z_{ij} \leq X_j \ \ \forall\, i, j \quad (2)$$

$$\sum_j Z_{ij} \leq 1 \ \forall\, i \quad (3)$$

$$d_{ij} Z_{ij} \leq 1.00 \ \ \forall\, i, j \quad (4)$$

$$\sum_j X_j = P \quad (5)$$

$$X_j \in \{0,1\} \ \forall\, j \quad (6)$$

$$Z_{ij} \in \{0,1\} \ \forall\, i, j \quad (7)$$

The objective (1) is to maximize the population covered and minimize the travel time between a ZCTA and its assigned trauma center. A large constant (M) is used as a delimiter in respect to minimizing the travel times to ensure that the closest trauma center is chosen for each ZCTA. I chose M to be (20,000), as it is a large enough number to bring the value close to zero. Constraint (2) prohibits a ZCTA node from being considered “covered” by a trauma center if a trauma center is not located there. Constraint (3) allows for each ZCTA to only be covered by a maximum of one trauma center. Constraint (4) requires that the travel time for a ZCTA node covered by a trauma center location be less than or equal to an hour. Constraint (5) requires that exactly P number of trauma centers be located. Constraints (6) and (7) are binary constraints for the decision variables.

Following the analysis of the effectiveness of the current state of the Arkansas trauma system, the next step was determining an optimal location configuration that would service the same amount of population. The set of potential trauma centers in this model include only existing hospitals that have met the trauma center qualifications. As a result, only the creation of a new trauma center would solve the problem of covering these ZCTAs that are not currently covered. For this reason, the fourteen ZCTAs that are not covered by the current trauma system were removed from the data. These nodes would be analyzed later to determine how their demand needs could be met.

The first optimization model that was run used the current 71 trauma centers as the constraint for the number of facilities to be located, so that the model could be checked for correctness and the data could be used as a basis to analyze other scenarios. Constraint (5) was altered each time a model was run to determine the demand covered for the specified number of located facilities. Models were run until a break-even point was found in terms of the number of trauma centers necessary to service the same population currently being served. It was determined that the same population could be covered with only 31 of the 71 existing trauma centers. The current system is shown in Figure 1, and the optimal solution serving the same population is shown in Figure 2.

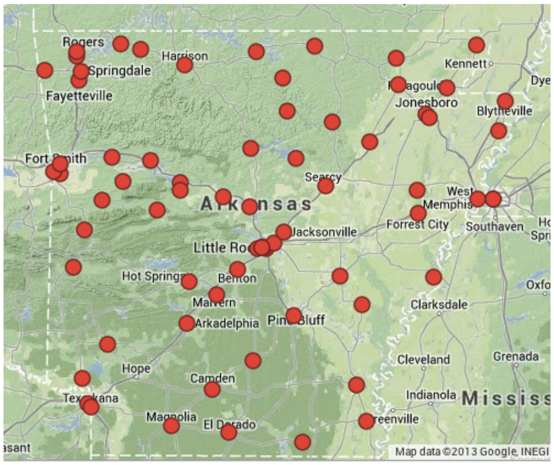

Figure 1: Map of Current System

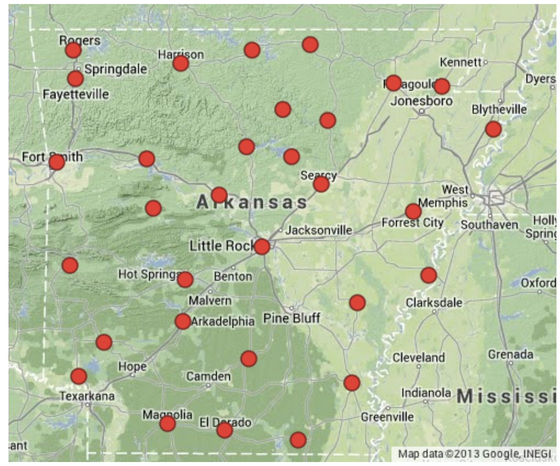

Figure 2: Map of Optimal System

The specific assignment data for each of the alternatives was read into Excel for each of the tested number of trauma center locations, but specific attention was paid to the optimal and current solutions. The current average time to reach the closest trauma center is 26 minutes (Table 3). With 40 less trauma centers in use, the average time to reach the closest trauma center increases to 31 minutes (Table 4). An interesting observation is the dramatic increase in number of ZCTAs that are assigned to higher-level trauma centers. In the current scenario, only five ZCTAs are most closely located to a Level I trauma center; however, in the optimal scenario, 47 ZCTAs are most closely located to a Level I trauma center (Tables 3 & 4). This change in level occurred because a large number of Level III and Level IV trauma centers were eliminated in the optimal configuration.

Current Trauma System Results	
Average Minimum Time (h:mm)	0:26
# of ZCTAs Assigned to Level I	5
# of ZCTAs Assigned to Level II	43
# of ZCTAs Assigned to Level III	188
# of ZCTAs Assigned to Level IV	346

Table 3: Results for Current Trauma System Assignments

Optimal Trauma System Results	
Average Minimum Time (h:mm)	0:31
# of ZCTAs Assigned to Level I	47
# of ZCTAs Assigned to Level II	33
# of ZCTAs Assigned to Level III	174
# of ZCTAs Assigned to Level IV	328

Table 4: Results for Optimal Trauma System Assignments

In the optimal trauma center location configuration, 88 ZCTAs saw an increase in the level of trauma center they were assigned to, and 36 saw a decrease in the level of trauma center they were assigned to (Tables 5 & 6). The ZCTAs that were assigned to a higher level of care in the new configuration saw an average level increase of 1.56; however, their average minimum time to reach these higher-level trauma centers increased by 12 minutes (Table 5). The ZCTAs that were assigned to a lower level of care in the new configuration saw an average level decrease of 1.25, and an average increase of 15 minutes in the minimum time to reach these lower-level trauma centers (Table 6).

ZCTAs With Increase in Assigned Trauma Center Level	
# of ZCTAs with increase in Trauma Center Level	88
Average decrease in Trauma Center Level	1.56
Average time increase (h:mm)	0:12

Table 5: Analysis of ZCTAs with Increase in Assigned Trauma Center Level

ZCTAs With Decrease in Assigned Trauma Center Level	
# of ZCTAs with decrease in Trauma Center Level	36
Average decrease in Trauma Center Level	-1.25
Average time increase (h:mm)	0:15

Table 6: Analysis of ZCTAs with Decrease in Assigned Trauma Center Level

Discussion

The intention of this research was to evaluate the suitability of the current trauma system in the state of Arkansas. The initial stages evaluated whether the current location configuration allowed for a patient located anywhere within the state to reach a trauma center within 60 minutes. It was determined that 14 of the 596 ZCTAs did not meet this requirement. The location of these ZCTAs can be referenced on a map of Arkansas in Figure 3.

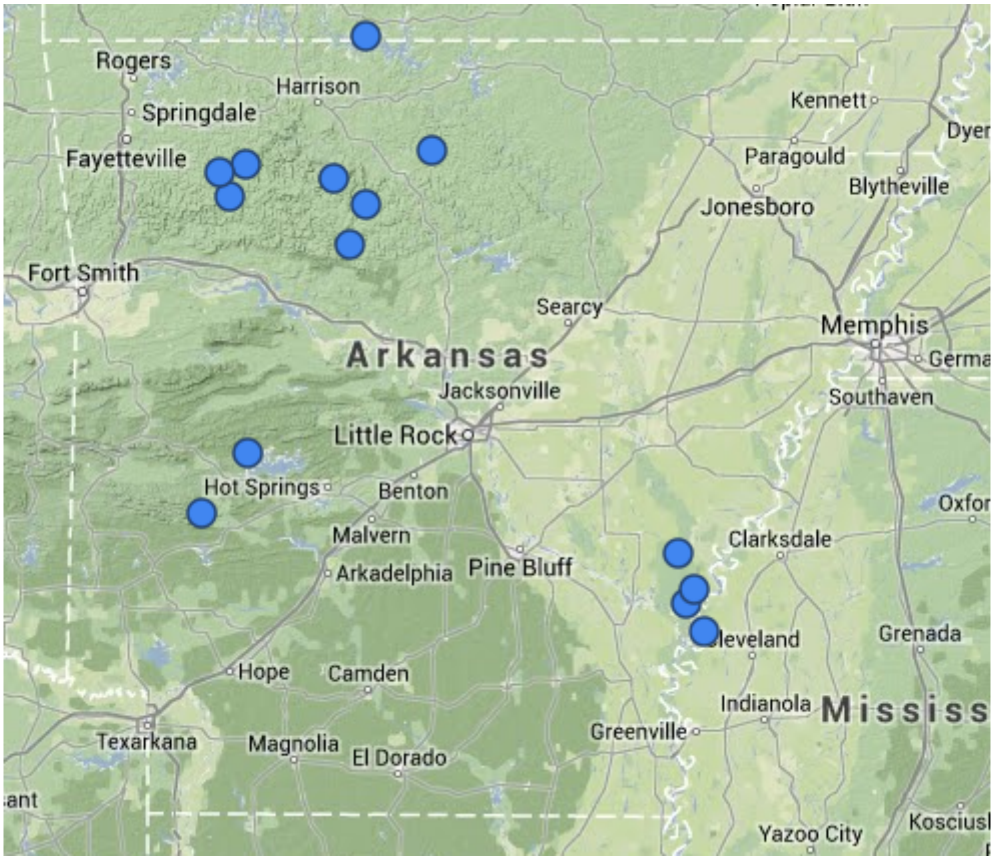

Figure 3: Map of Current Uncovered ZCTAs

To service these areas, additional trauma centers need to be added to the system. The map indicates that the uncovered ZCTAs create three "clusters" of areas that could be serviced with their own individual trauma centers. Potential trauma center locations for each of these areas can be seen on a map in Figure 4. The acquisition of the resources required to create these trauma centers will be discussed further when the optimal location configuration is addressed.

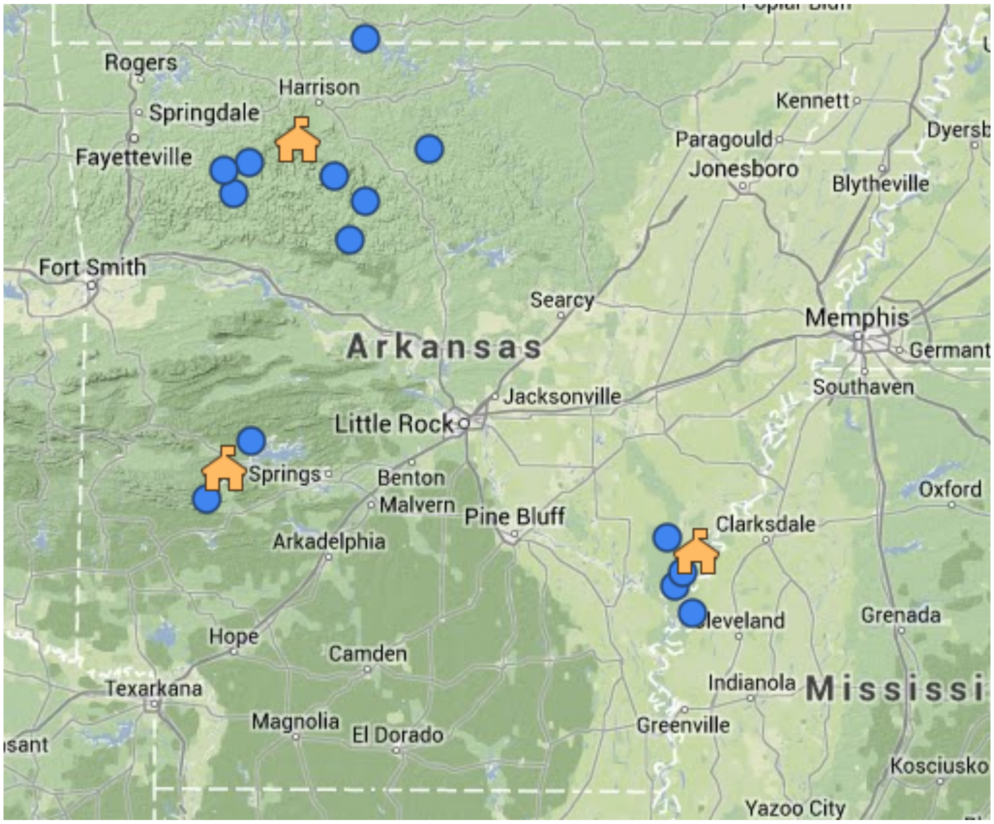

Figure 4: Potential Trauma Center Locations

The latter stages of this research explored the optimal trauma center location configuration that would serve the same population as the current trauma system. The current system serves 2,911,876 people, or 99.666% of the population, with 71 trauma centers. This exact same population can be served with only 31 trauma centers. Although the argument can be made that the current system covers nearly all of Arkansas' population, when it comes to health services, 100% of the population needs to have the ability to reach a trauma center. There are a variety of implications resulting from the fact that the optimal configuration requires less than half of the current trauma centers to be open. Resources from the unnecessary trauma centers can be reallocated to other, more essential, trauma centers. These resources could also be used to open up trauma centers in areas that are not currently serviced.

In regards to the use of the resources from unused trauma centers in the optimal configuration, the option of closing these centers and using the funds to enhance other centers needs to be explored. There are only five Level I trauma centers in the Arkansas trauma system. Two of these are outside of the state (in Memphis and in Springfield), and another two of them are children's hospitals. The University of Arkansas for Medical Sciences (UAMS) is the only Level I trauma center within the state of Arkansas that can serve any patient's needs. Further analysis could, and should, be conducted to see whether allocating the funds from closed trauma centers to open trauma centers could increase their trauma level rating and better serve the residents of Arkansas.

A methodological weakness within this research deals with the modeling of the population distribution as Zip Code Tabulation Areas. Beyer et. al. (2011) recognized that the need to estimate the distance from an individual to a service provider is common in public health research. To protect confidentiality, ZCTAs or Zip Codes are typically used, but these methods are often imprecise. This research proposed a methodology that utilizes an algorithm known as "the probabilistic sampling method" (PSM). The PSM has a number of benefits over the traditional geocoding approach used in this research. This methodology improves the precision of estimates of geographic access to health services, or trauma centers in this case (Beyer et. al. 2011). This research could be improved upon by implementing the PSM algorithm as an alternative to the geocoding approach used.

Another aspect that could be explored in further research is determining which levels of trauma centers are assigned to each ZCTA. This model formulation focused only on maximizing the population covered by these trauma centers, while minimizing the distance from a ZCTA to its assigned trauma center. An additional component could explore minimizing the level of a trauma center assigned to a ZCTA (which maximizes potential care), instead of focusing purely on minimizing the distance from a ZCTA to a trauma center.

Conclusions

This research proposed to explore existing quantitative criteria for trauma center location planning, and to use these criteria to evaluate the current state of the trauma system in Arkansas. In-depth analysis resulted in the ability to evaluate the effectiveness of Arkansas's current system. Optimization models were then created to evaluate the current system in relation to an optimal system generated by the mathematical models. All of this analysis provided insight not only into the state of the current system, but also as to how future changes could be made. The exact population currently being served by the Arkansas trauma system could be served with less than half of the existing trauma centers. The resources from the extraneous trauma centers could be utilized in more efficient ways to better meet the needs of the people of Arkansas. With this trauma system framework having been so recently enacted, the analysis of the suitability of the trauma center location configuration is important. It has not yet been adequately assessed, and this research allowed for the evaluation of the system and recommendations for how to improve the effectiveness of trauma care throughout the state.

Appendices

Tabulation Matrix		Trauma Center Locations			
		Arkansas Children's Hospital		Le Bonheur Children's Hospital	
ZCTA	Latitude, Longitude	34.743074, -92.291771		35.14361, -90.031875	
		Distance (miles)	Time (hours, minutes)	Distance (miles)	Time (hours, minutes)
Arkansas - ZCTA 38769 (part)	33.864775, -90.985297	181	3:10	120	2:06
Arkansas - ZCTA 65729 (part)	36.51396, -92.592739	173	3:31	229	4:10
Arkansas - ZCTA 65733 (part)	36.527116, -92.849419	165	3:42	247	4:23
Arkansas - ZCTA 65761 (part)	36.576449, -92.724984	187	3:36	234	4:04
Arkansas - ZCTA 71601	34.179353, -91.892651	57.9	1:00	152	2:40
Arkansas - ZCTA 71602	34.265166, -92.145566	36.9	0:39	173	2:38
Arkansas - ZCTA 71603	34.121075, -92.088127	49.6	0:50	158	2:41
Arkansas - ZCTA 71630	33.620304, -91.207069	120	2:02	178	3:18
Arkansas - ZCTA 71631	33.580025, -92.264958	90.7	1:42	206	3:35
Arkansas - ZCTA 71635	33.130555, -91.99661	138	2:31	223	3:58
Arkansas - ZCTA 71638	33.520939, -91.484745	117	2:02	182	3:17
Arkansas - ZCTA 71639	33.901476, -91.520374	90.7	1:32	154	2:50
Arkansas - ZCTA 71640	33.101218, -91.278079	147	2:33	182	3:13
Arkansas - ZCTA 71642	33.387395, -91.887479	116	2:06	210	3:46
Arkansas - ZCTA 71643	34.016891, -91.576497	77.3	1:15	171	2:55

Figure A1: Excerpt of Parsed Distance Matrix Results

```
#OPTIMIZATION MODEL

#SETS--------------------------------------------------------------------------
set I; #Set of ZCTAs, i
set J; #Set of TC Locations, j

#PARAMETERS--------------------------------------------------------------------
param pop{i in I}; #population of ZCTA i
param travel{i in I, j in J}; #travel time between ZCTA i and TC Location j

#VARIABLES---------------------------------------------------------------------
#X_j = 1 if TC is located at TC Location j; 0 otherwise
var X{j in J} binary;

#Z_ij = 1 if ZCTA i is covered by TC Location j; 0 otherwise
var Z{i in I, j in J} binary;

#OBJECTIVE---------------------------------------------------------------------
maximize population_covered: sum{i in I, j in J} ((pop[i]*Z[i,j]) - ((1/20000)*(travel[i,j]*Z[i,j])));

#CONSTRAINTS-------------------------------------------------------------------
subject to

#ZCTA cannot be covered by a TC Location if it is not located there
ZCTA_covered{i in I, j in J}: Z[i,j] <= X[j];

#Each ZCTA need only be covered once
ZCTA_once{i in I}: sum{j in J} Z[i,j] <= 1;

#Travel time for a ZCTA covered by a TC Location must be <=1.00 hours
travel_time{i in I, j in J}: travel[i,j]*Z[i,j] <= 1.00;

#Limit the number of TC Locations
TC_max: sum{j in J} X[j] = 30;
```

Figure A2: AMPL Optimization Model

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