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GIS-Based Route Risk Assessment of Hazardous Material Transport

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GIS-Based Route Risk Assessment of Hazardous Material Transport

by

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GIS-Based Route Risk Assessment of Hazardous Material Transport

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The transportation of hazardous materials keeps increasing across the United States due to the growing consumption of goods and rising need for manufactured materials. Furthermore, concerns are mounting over the safe surface transportation of hazardous materials. Highways and rails are the most common modes of transport for hazardous materials, although the risk posed from highway transport of hazardous materials may be higher due to the fact that highways are public while rails are mostly private. The majority of hazardous material cargo is carried on the highway network by trucks. Due to possible adverse effects on human and animal populations in the event of an accident involving hazardous materials, there is a need for the development of a highway route risk assessment tool that precisely represents transportation risks associated with hazardous cargos and to build a framework for designating a set of risky routes based on different factors.

The research presented in this thesis explains a methodology to analyze the spatial patterns of truck accident data, discern potentially risky routes of truck traffic carrying

hazardous materials, and estimate the impact area of an identified risky route by quantifying the human population affected in that area. Lancaster County in Nebraska was used as the study area and the hazardous material exposure from a theoretical truck-involved accident was estimated. It was concluded that the developed procedures successfully identified vulnerable areas in terms of hazardous material transport and estimated the affected areas and human population.

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1 INTRODUCTION

1.1 Background

Hazardous materials (hazmats) are substances that can adversely affect human health and the environment. They are classified as explosives, flammables, oxidizing substances, poisonous gases or radioactive materials (United Nations, 2001). However, in a broad sense, hazmats can be substances whose physical or chemical traits can harm living organisms including humans (ABAG, 1990). A modern society ceaselessly requires and generates hazmats, which require safe handling and transport. Thus, safe treatment of hazmats has been a serious concern of society.

According to the US Department of Transportation (USDOT), more than half of the total hazmat tonnage (53.9%) was carried by trucks on the highways (US DOT, 2010). The release of hazmat from a roadway accident is a serious threat to those in the vicinity of the accident location. As circumstances require, evacuation plans may be implemented at the affected areas. Therefore, it is important to identify areas that may be vulnerable in terms of hazmat accidents.

Identification of highways that may be susceptible to hazmat crashes is an important first step toward more informed planning for hazmat accidents. This research focused on developing procedures and a tool for identification of vulnerable highway segments and surrounding areas with respect to hazmat incidents. Identification of susceptible highways and surrounding areas can help policymakers, engineers, and stakeholders with more informed decision-making and better planning for dealing with hazmat accidents.

This research utilized several publically-available datasets and GIS-based data integration techniques. The basic premise was that each input datum had intrinsic characteristics that represented suitable or unsuitable degrees for the research purpose (Murphy, 2005). Diverse input datasets (roadway networks, wind information, hazmat facilities, fire stations, medical facilities, schools, and population data) were obtained from public sources. In addition, four years of traffic accident data were obtained from the Nebraska Department of Roads (NDOR) to identify accident-prone highway segments for truck traffic. Spatial analytical concepts were utilized to discern patterns among truck accidents. The spatial analysis revealed useful accident point patterns which were then used in the integration of all the datasets. Combining all the datasets together allowed identification of highway segments satisfying multiple selection criteria. That is, the most vulnerable highway segments in terms of all the hazmat risk-related criteria were identified. The hazmat modeling tool was used to portray release pattern in the air. This provided a general view of hazmat dispersion patterns and the affected areas by the dispersion shapes.

This thesis presents a concise description of the specific issues investigated in this research in a problem statement section. The sections after the problem statement include the research area selection, research objectives, research organization, data collection, data analysis, and conclusions.

1.2 Problem Statement

A significant amount of hazmat flows through Nebraska using the highway system and presents varying levels of hazmat exposure to areas along the highways. Currently, there is no assessment of the risk associated with the flow of hazmat on different Nebraska highway segments, including estimation of vulnerable populations in case of hazmat accidents on highways. Also, research techniques using multiple criteria in conjunction with statistical approaches using historical accident data have not been fully utilized. Thus, an investigation of the development of a geographic information system (GIS) based tool for assessment of risk on different Nebraska highway segments utilizing multi-criteria analysis that takes into consideration historical truck accident data is warranted.

1.3 Research Area Selection

To develop and test a GIS-based risk assessment tool for identification of hazmat risk on different Nebraska highway segments, areas with high truck traffic were selected. An estimate of the annual vehicle miles traveled by trucks (AVMTT) in Nebraska was considered an indicator for research area selection. AVMTT can be calculated by multiplying the distance by the Average Annual Daily Truck Traffic (AADTT). AADTT was computed using the American Association of State Highway and Transportation Officials (AASHTO) method. This method has three steps:

1) Average monthly days of the week (MADW) are computed. There are 84 values (12 months by 7 days).
2) The values are then averaged to yield the seven average annual days of the week (AADW).
3) These seven values (AADW) are then averaged to yield the AADT.

To derive the statewide AVMTT for only hazmat trucks, the portion of hazmat trucks in the traffic stream was required and obtained using the steps below.

1) The State of Nebraska was divided into 8 sections.
2) Each section had four truck traffic observation sites and 12-hour observations were collected at each site to count non-hazmat as well as hazmat trucks by hazmat classifications.
3) Roadways where the observation sites were located were categorized by different road groups.
4) NDOR adjustment factors for each road group were applied to convert 12-hour truck traffic data into annual average daily truck traffic and annual average daily hazmat truck traffic counts.

Lancaster County in Nebraska was selected as the research area because it had one of the highest numbers of AVMTT for hazmat trucks, and the second highest number of total AVMT. While Lincoln and Dawson Counties had higher AVMTT for hazmat trucks (Table **1**), these two counties had lower numbers for total AVMT. Thus, it was appropriate to choose Lancaster County as the research area for analysis. Table 1 shows the top ten AVMTT for hazmat trucks in Nebraska.

Table 1: Top 10 AVMTT for hazmat trucks in Nebraska

Rank	County	2010 Hazmat Truck AVMTT (millions)	2010 Total AVMT (millions)
1	Lincoln	8.56177	587.069
2	Dawson	6.889472	420.179
3	**Lancaster**	**4.967357**	**2361.797**
4	Douglas	4.760417	4432.422
5	Buffalo	6.000548	592.996
6	Keith	3.351206	305.761
7	Hall	4.722522	622.849
8	Seward	3.371577	377.335
9	York	3.341434	350.771
10	Hamilton	3.998482	291.613

1.4 Research Objectives

The research objective was to develop a GIS-based multi-criteria tool for identification of risk-prone highway segments for hazmat-involved highway accidents. Due to limitation of resources, consideration of all roadways in Nebraska for potential hazmat vehicle accidents was not practical and therefore, only major highway segments in Lancaster County were taken into consideration. Additionally, this research focused on identifying affected areas and resident populations that may potentially be affected by released hazmat from a highway accident. According to chemical concentration levels from the source point, different boundaries lines were set. These lines could be used for evacuation plans in case of a hazmat release accident. Unlike using a circular boundary line, the research introduced a modeling tool for hazmat release patterns to portray the footprints of hazmat dispersion more accurately.

1.5 Research Plan

The research plan consisted of four main tasks, which are explained in each chapter of the thesis. A brief summary of each task is presented in sections 1.5.1-1.5.4.

1.5.1 Task 1: Literature Review

A literature review was conducted to provide current trends and statistics on hazmat transportation and accidents. This review task identified a general description of hazmat, shipments, number of hazmat-related accidents, hazmat transportation risk, impact area modeling, and multi-criteria analysis for hazmat transportation. The literature review section provides related research with respect to hazmat transportation, related problems, identifies the limit of current studies, and justifies this research.

1.5.2 Task 2: Data Collection

Several datasets were retrieved from diverse sources for multi-criteria analysis. Most data were obtained from official government websites free of cost. The collected data included roadway network data; wind information; locations of hazmat facilities, fire stations, medical facilities and schools; four year period vehicle accident data; and population data in Lancaster County. Nebraska truck accident data were obtained from NDOR. Chapter 3 presents data collection details.

1.5.3 Task 3: Data Analysis

As part of this research three data analyses were conducted in GIS: a truck accident data analysis, a multi-criteria analysis, and an impact assessment analysis. The historical accident data were analyzed to be utilized in the multi-criteria analysis. Microsoft Excel software was used to extract truck-involved accidents from the accident data. Next, different criteria or layers were posed in a GIS platform for integration. The cell-based raster analytical concept was used to meet the different criteria. Finally, an impact assessment analysis was implemented to quantify the impact areas and population.

1.5.4 Task 4: Conclusions

This task consisted of drawing conclusions based on the results of each analysis and discusses the implications. Also, future research topics related to the studies in this thesis are presented.

1.6. Thesis Organization

Following this chapter is a chapter on literature review that presents published literature relevant to this research, including a general description of hazardous materials, hazmat shipments, hazmat transportation accidents, hazmat transportation risk, impact area modeling, and multi-criteria analysis for hazmats.

Chapter 3 presents data collection details such as where and how the data were collected, including explanations of each datum and their relevance to the research objectives. Chapter 4 presents the data analysis in which some of data were utilized directly while others, such as truck accident data, were analyzed with spatial analytical techniques to create more meaningful datasets. There are three main analysis parts in this chapter. They include truck accident data analysis, multi-criteria analysis, and impact analysis. A truck accident data analysis was conducted to create an accident density raster map, which was one of the inputs to multi-criteria analysis. In the multi-criteria analysis, all the inputs collected from different sources and the results of an accident data analysis were integrated to determine areas where all the criteria were met. The impact analysis showed the procedure to get both visual illustrations of impact and the quantification of the impact area.

Chapter 5 presents the research conclusions that are based on information gained from the data analysis section. The chapter also includes information on the limitations and challenges of this research to adduce future directions of related studies.

2 LITERATURE REVIEW

2.1 General Descriptions of Hazardous Materials

The Association of Bay Area Governments (ABAG) defined a hazardous material (hazmat) as “a harmful substance that can cause injury, death or serious illness, or put a substantial threat to the human population or the environment due to its chemical, physical or infectious attributes” (ABAG, 1990). The United Nations (2001) classified hazardous materials into nine different hazmat classes, using their physical, chemical, and nuclear properties. They were: explosives and pyrotechnics; gasses; flammable and combustible liquids; flammable, combustible, and dangerous-when-wet solids; oxidizers and organic peroxides; poisonous and infectious materials; radioactive materials; corrosive materials (acidic or basic); and miscellaneous dangerous goods, such as hazardous wastes. The USDOT used the same classifications for their Commodity Flow Survey (CFS). Table 2 shows the classification used for the survey. However, as defined by ABAG, hazmat can be any substance whose physical or chemical traits can harm living organisms, including humans. The United States Environmental Protection Agency (USEPA) and the California Department of Toxic Substance Control (DTSC) have been updating the list of classifications.

Table 2 USDOT Hazardous Material Classes

Class	Properties of Hazardous Materials
1	Explosives
2	Gases
3	Flammable and combustible liquids
4	Flammable solids
5	Oxidizers and Organic Peroxides
6	Toxic (Poisonous) Materials and Infectious Substances
7	Radioactive Materials
8	Corrosive Materials
9	Miscellaneous Dangerous Goods

2.2 Hazardous Material Shipments

There were approximately 500,000 daily hazmat shipments reported in the US (Dungun, 1991). The Office of Hazardous Materials Safety (OHMS, 1998), or the affiliated organization Pipeline and Hazardous Materials Safety Administration (PHMSA), which was created within the USDOT in 2004, estimates that there were more than 800,000 hazmat shipments per day in the US. According to OHMS, about 43% of total hazmat tonnage is transported by truck and approximately 94% of the total number of hazmat shipments were made by trucks while air, rail, and water transportation accounted for 5.3%, 0.53%, and 0.04% respectively (OHMS, 1998). Pipelines accounted for only 0.11% of the total hazmat trips.

Dependence on trucks for hazmat transportation increased in 2002 and 2007 compared to 1998 in terms of the percentage of tons shipped. A Commodity Flow Survey (CFS) conducted by USDOT revealed that 52.9% and 53.9% of total hazmat tonnage was carried by trucks, followed by pipelines (30.2% and 28.2%) in 2002 and 2007 respectively shown in Table 3 (USDOT, 2010). Even though the percentage changed within narrow limits between 2002 and 2007, large amounts of hazardous materials were mainly transported by trucks using the highway system.

Table 3 Hazardous Material Shipment Characteristics by Mode of Transportation: 2007 and 2002

Source: USDOT, 2010

Mode of transportation	**Tons (thousands)**		**Percentage of Tons**	
	2007	2002	2007	2002
Truck	1,202,825	1,159,514	53.9%	52.9%
Rail	129,743	109,369	5.8%	5.0%
Water	149,794	228,197	6.7%	10.4%
Pipeline	628,905	661,390	28.2%	30.2%
Multiple modes	111,022	18,745	5.0%	0.9%
Other and unknown modes	8,844	14,304	0.4%	0.6%
Total	**2,231,133**	**2,191,519**	**100.0%**	**100.0%**

2.3 Hazardous Material Transportation Accidents

Erkut et al. (2007) argued that even though a hazmat incident was a rare event, the potential consequences of such an incident were high. The USDOT (2013) reported that there were 15,774 incidents involving hazmat transportation in 2013, of which 26.5% were during the transit phase and it was noticeable that damages in the transit phase accounted for 94.6% of the total damages in 2013. That is, en-route damage was the largest portion, representing $67.06 million. Table 4 shows the 2013 hazmat incident summary by transportation phase.

Table 4: U.S. Hazmat Incident Summary by Transportation Phase in 2013

Source: PHMSA, 2014

Transportation Phase	Total Incidents	Total number of Hospitalized Persons	Total number of Non-Hospitalized Persons	Total Fatalities	Total Damages
In transit	4,184	11	37	9	$ 67,056,517
In transit storage	483	8	0	0	$ 562,306
Loading	3,350	3	22	1	$ 2,836,118
Unloading	7,757	5	68	0	$ 454,873
Total	15,774	27	127	10	$ 70,909,814

PHMSA also provided hazmat accident information from the Incident Reports Database. The database contained all reported hazmat-related accidents since 2000, when such record-keeping started. Since 2000, there were 246,814 hazmat accidents. Figure 1 shows the hazmat accident classification from 2000 to 2014. It is noticeable that flammable-combustible liquids and corrosive materials accounted for the major portion of hazmat accidents during the period.

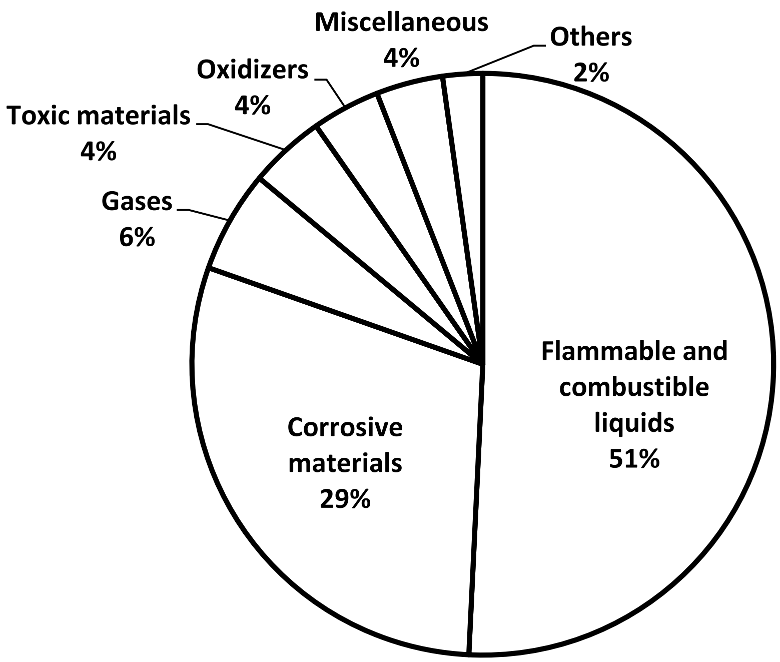

Figure 1 Hazmat Accidents by Class (PHMSA, 2014)

Source: https://hazmatonline.phmsa.dot.gov/IncidentReportsSearch/

2.4 Hazmat Transportation Risk

Hazmat transportation risk is distinguishable from normal transportation accident risk since it may cause serious consequences to surrounding communities. Erukt et al. (2007) maintained that the main factor that distinguished hazmat transportation issues from other transportation problems was the risk. List et al. (1991) used the following equation to calculate the total risk from hazmat movement on a highway link:

$$R_l = S_l \times P_l \times N_l$$

Where,

R_l = the total risk from hazmat movement on link l,

S_l = the number of shipments on link l,

P_l = the probability of a hazmat release accident for a single shipment on link l, and

N_l = the total number of persons who will be affected by a release accident on link l.

Alp (1995) defined hazmat transportation risk as the measure of the probability and severity of damages to exposed receptors with respect to the hazmat-related transportation accidents. The exposed receptor could be anything such as a person, the environment, or properties near an accident spot (Erukt et al., 2007). That is, anything whose ability or function can be deteriorated by hazmat transportation release accidents was considered for calculation of hazmat transportation risk. In terms of consequences, Erukt el al. (2007) classified four different categories: human-related effects, including death, injury, or long-term effects of the hazmat exposure; property damages; environmental effects, including animals and plants; and socio-economic losses due to evacuation and blockage of affected roadway segments.

2.5 Impact Area Modeling

There is significant literature that discusses modeling of impact areas by hazardous materials. Erkut et al. (2007) explained that the negative consequences in terms of hazmat transportation accidents are a function of the impact area and the affected population, property, and environmental resources. They maintained that the shape and the size of the hazmat impact area can be determined by hazmat types, topology, weather, and wind direction and speed.

To estimate the impact area, different shapes and methods were used. Batta and Chiu (1988) and ReVelle et al. (1991) suggest a method to estimate the affected area by drawing a band of fixed width around each link and using the number of persons living within this band as the link consequence. For their approach, there was an assumption that all people living within the band would experience the same impact from the accident and people outside of the band would not be impacted. Erkut and Verter (1998) and Kara et al. (2003) used a “danger circle” centered on the hazmat accident point and calculated the affected areas within the “danger circle.” The radius of the circle was determined by the type of hazmat. Rectangles were also considered to model hazmat transportation impact area (ALK Associates, 1994). The “danger circle” or the rectangular model did not consider wind direction, resulting in a constant distance from the accident points. To model the impact of wind, the Gaussian plume model (GPM) was popularly utilized for impact areas due to its reliable reflection of airborne hazmat accidents (Patel and Horowitz, 1994; Chakraborty and Armstrong, 1995; Zhang et al., 2000). Figure 2 shows the shape of each described model.

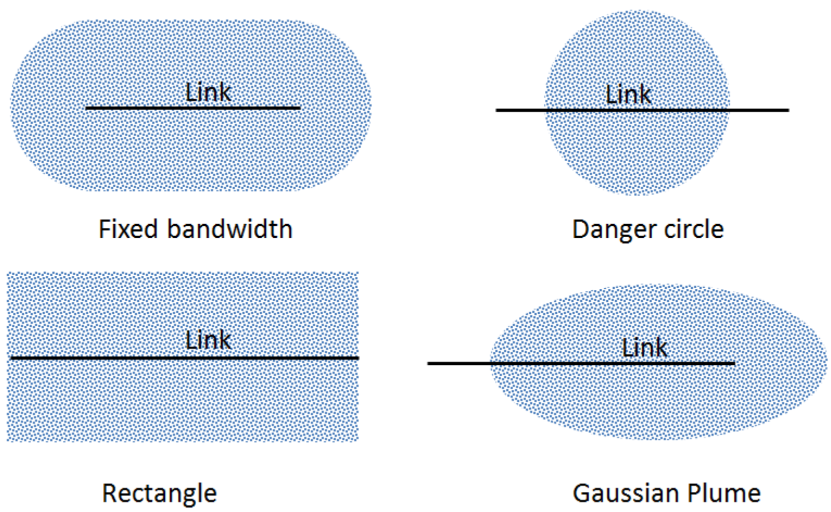

Figure 2 Impact Area Modeling Types around the Route Segments

To model an airborne hazmat such as chlorine and ammonia, many researchers opted for GPM (Hanna et al., 1993; Patel and Horowitz, 1994; Chang et al., 1997; Zhang et al., 2000; Puliafito et al., 2003). The basic equation for GPM is:

$$C(x,y,z) = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left(\frac{-y^2}{2\sigma_y^2}\right)\left\{\exp\left(\frac{-(z-h)^2}{2\sigma_z^2}\right) + \exp\left(\frac{-(z+h)^2}{2\sigma_z^2}\right)\right\}$$

Where:

C =the concentration of the emission,

Q = the quantity of the emission,

u = the wind speed,

h = the height of the source above ground level,

σ_y and σ_z = the standard deviations of a statistically normal plume in the lateral and vertical dimensions.

The model considers dispersion in all three dimensions (x, y and z), but Erkut et al. (2006) maintained that the model could be simplified for hazmat dispersion from traffic accidents. Since the source of hazmat is on the ground, the z value, or the height of the source, is zero. This creates a new simplified equation as follows:

$$C(x,y,z) = C(x,y) = \frac{Q}{\pi u \sigma_y \sigma_z} \exp\left(\frac{-y^2}{2\sigma_y^2}\right)$$

Erukt et al. (2007) pointed out several assumptions under the Gaussian Plume model:

(1) The traits of airborne contaminants were kept during dispersion,

(2) The topology was assumed flat,

(3) The released gas was carried only by the air, and not absorbed by soil or plants,

(4) The wind was blowing at a constant speed and in the same direction, and

(5) The spillage rate was constant.

The authors indicated that these limiting assumptions might make the model impractical, resulting in inaccurate results. For example, if a hazmat release accident occurred in a geographically hilly area, the real release pattern of hazmat will be different from the created plume model.

2.6 Multi-criteria Analysis for Hazmat Transportation

Multiple-criteria analysis (MCA) originates from operations research, which considers diverse criteria to determine the optimal decision. MCA has been popular for making more informed decisions. MCA can be a useful approach for a hazmat transportation routing analysis since many different factors affect the risk of a hazmat release accident on highways. By considering different criteria together, it is possible to identify high-risk hazmat transportation routes.

Lepofsky and Abkowitz (1993) conducted multi-criteria analysis, calculating the impact of hazmat transportation. They discussed possible Geographic Information Systems for Transportation (GIST) techniques for analysis of hazmat transportation and hazmat incident management by using different routing criteria such as distance, travel time, population exposure, and so on. They applied the techniques in several case studies in California to demonstrate the feasibility of the technique, and indicated the importance of weights on different criteria, since using different weights often give different results.

Panwhar et al. (2000) presented a multi-criteria risk assessment system for hazmat transportation based on a GIS. They developed the system to determine the optimized route that minimizes hazmat transportation risk. In the system, the optimized route did not necessarily have the best score for all the criteria because the route with the best averaged score was chosen.

Leonelli et al. (2000) considered MCA routing models to select less dangerous routes for hazmat transportation. In the research, they analyzed an optimization problem between vehicle operating costs and risk-related costs. If routes were selected to minimize hazmat accident risks only, the significantly longer routes that avoid all the vulnerable areas could be determined as the best hazmat transportation routing model. They argued that these senselessly long routes were feasible without taking into account appropriate vehicle operating costs. This indicated that multiple criteria were required for analysis. They also explained that diverse weights could be added based on various objectives and that the weights should mirror the relative importance of each criterion.

Van Raemdonck et al. (2013) argued that an allocation of weights to criteria approach causes a problem of subjective weight assignment that may produce varying results. In addition, Clark and Besterfield-Sacre (2009) maintained that previous studies using the multi-criteria analysis did not pay much attention to the statistical methods in which historical accident data are dealt. Abkowitz and Cheng (1988) also conclude that results may be more accurate if more quantitatively collected historical data were used in analyses.

3 DATA COLLECTION

Eight possible different datasets of Lancaster County with respect to hazardous material transportation were used in the analysis. These were the roadway network, wind speed map, location information of fire stations, medical facilities, school locations, hazmat facilities, 2008 to 2011 accident data, and 2010 population data for Lancaster County. Each dataset is explained in detail in sections 3.1 to 3.6.

3.1 Roadway Network in Lancaster County

The roadway network information was essential to identification of risky hazmat transportation routes. The National Highway Planning Network (NHPN) version 11.09 for Nebraska was used in this research. It is a 1:100,000 scale geospatial network database, and contains information on the National Highway System (NHS). The network system includes all principal arterials and rural minor arterials with respect to highway functional classes. Since the risk of major truck traffic carrying hazmat is higher on those high mobility-oriented roads, the arterials with different Annual Average Daily Traffic (AADT) in Lancaster County were classified and analyzed for different levels of risk. Figure 3 shows the arterials with different classes of AADT.

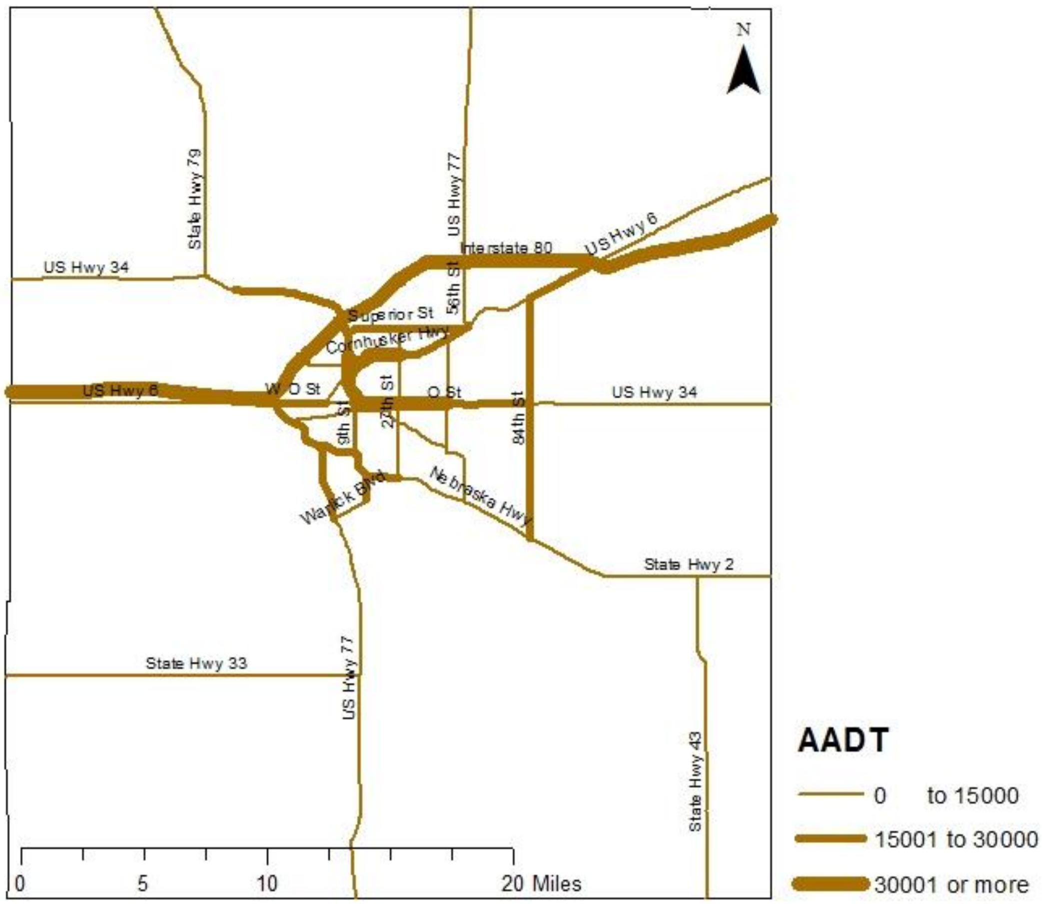

Figure 3 Three Different AADT Groups in Lancaster County

3.2 Wind Information

Wind speed and direction are an important consideration in the analysis of diffusion patterns of hazmat releases. If an area has higher wind speed, the risks of any hazmat released may be more significant since the rapid spread enlarges affected areas, on the other hand greater wind speed may help with the dispersal of any hazmat substance. The

US Department of Energy provides information on regional wind. Table 5 shows the classification and corresponding speeds at the elevation of 164.04 feet (50 meters).

Table 5: Wind Power Class

Wind power class	Resource potential	Wind speed at 50 m elevation (m/s)	Wind speed at 164.04 ft elevation (ft/s)
1	Poor	0.0 - 5.7	0.0 – 18.7
2	Marginal	5.8 - 6.5	18.8 – 21.3
3	Fair	6.6 - 7.2	21.4 – 23.6
4	Good	7.3 - 7.8	23.7 – 25.6
5	Excellent	7.9 - 8.2	25.7 – 26.9
6	Outstanding	8.3 - 9.0	27.0 – 29.5
7	Superb	> 9.1	> 29.6

Lancaster County only has four wind classes, which are shown in Figure 4. The prevailing wind speeds in Lancaster County range from 18.7 ft/s to 25.6 ft/s. It is notable that some regions in the south part of Lancaster County have relatively high wind speeds, which implies that any hazmat release may spread quickly. However, the areas showing strong wind have lower population density. Most of the areas in Lancaster County belong to category 2 Marginal (18.8 – 21.3 ft/s) and 3 Fair (21.4 – 23.6 ft/s) wind speeds.

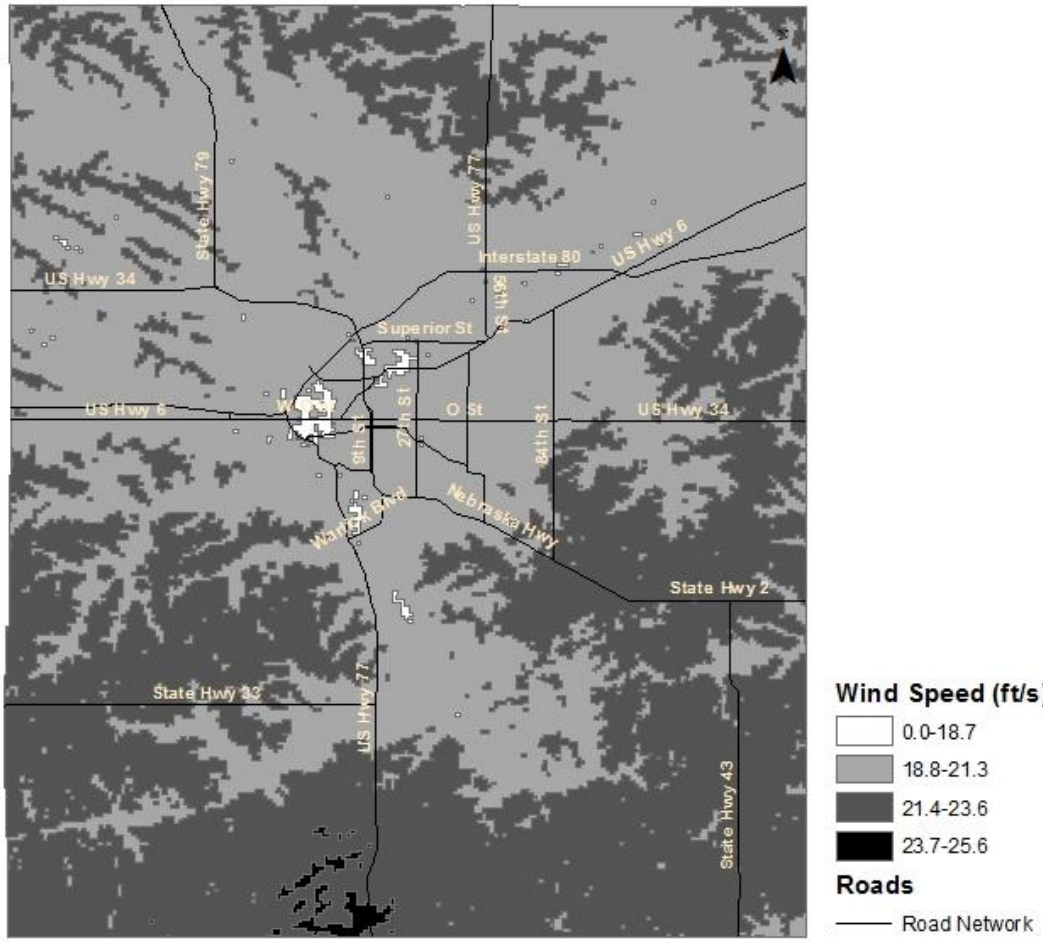

Figure 4 Wind Classes in Lancaster County

3.3 Hazmat Facilities in Lancaster County

The location of major hazmat facilities is an important factor to consider as hazmat accidents could occur at these facilities during loading and unloading. The US EPA has the Toxics Release Inventory (TRI) program, which provides information on the hazmat facility names, addresses, coordinates, chemical types, and quantities, etc. The 2010 data for Nebraska were downloaded from the inventory and used to locate hazmat facilities in

Lancaster County. The total 21 hazmat facilities in Lancaster County were geocoded using the coordinates of each facility. The detailed TRI geocoding information for hazmat facilities is provided in Appendix A. Figure 5 shows the locations of those hazmat facilities in Lancaster County. Areas around these facilities were deemed more dangerous due to the possibility of incidents during loading and unloading of hazmat.

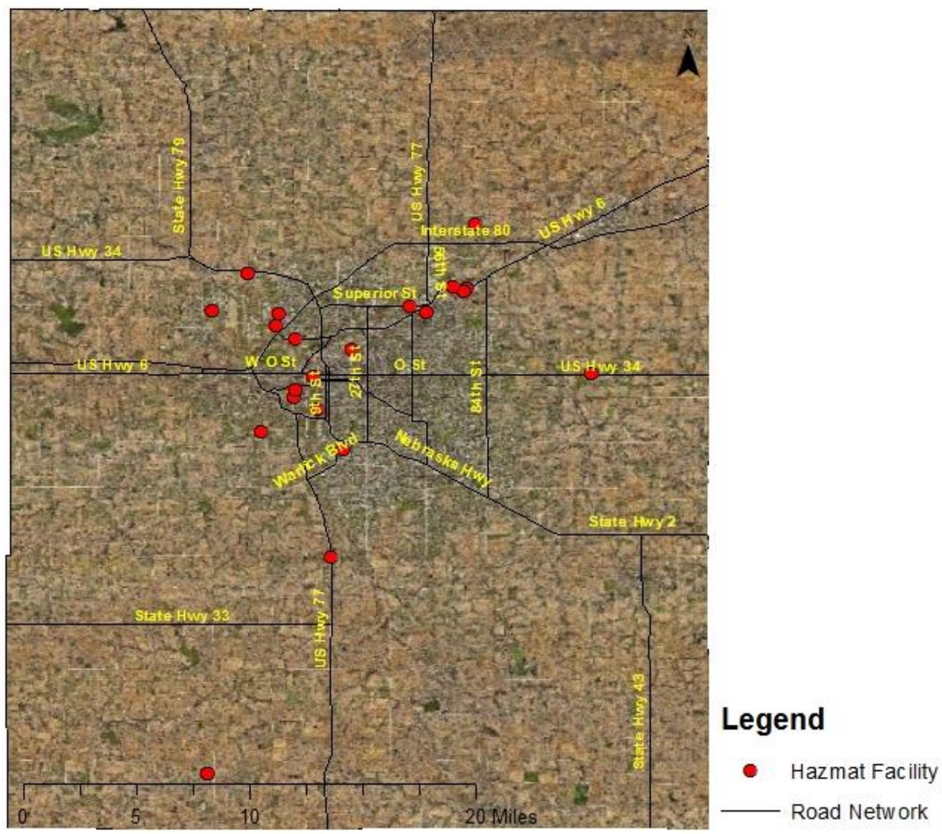

Figure 5 Hazmat Facilities in Lancaster County

Across the county, facilities storing different hazmats were mostly located along major arterials and avoided densely populated areas. Figure 6 shows the locations of hazmat facilities and housing units in the center of Lancaster County. It is notable that none of the hazmat facilities are included in areas that have more than 180 housing units. However, some areas near the hazmat facilities have moderate number of housing units.

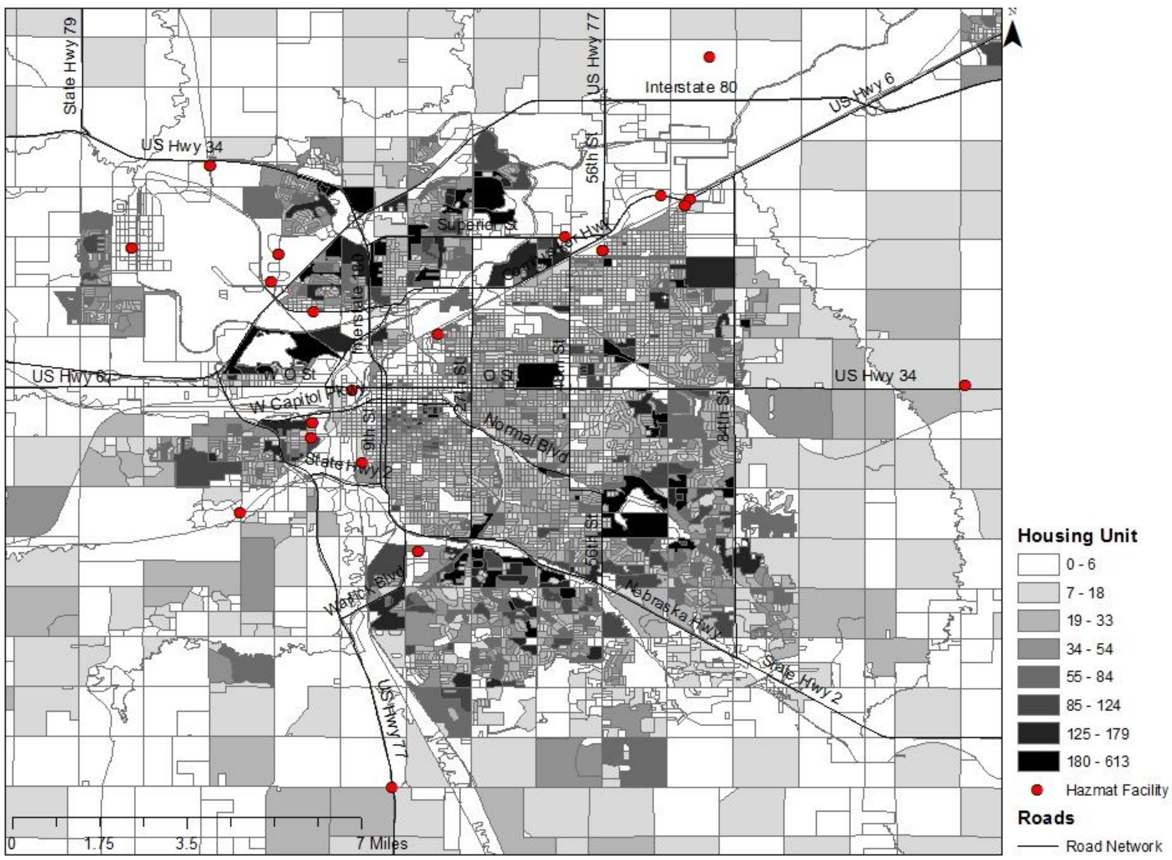

Figure 6 Locations of Hazmat Facilities and Housing Units

3.4 Fire Stations, Medical Facilities and Schools in Lancaster County

For risk analysis, the locations of fire stations, medical facilities, and schools were taken into consideration. It was assumed that areas closer to fire stations would have lower risk than areas farther from the stations because of greater response time to hazardous materials incidents. An area in close proximity to a fire station will have a lower hazmat risk due to quicker response. Similarly, nearby medical facilities could reduce the consequences of harmful spilled contaminants due to quick treatment for patients. However, areas close to schools were regarded to be riskier since people are more concentrated in schools and young students are more likely to be vulnerable to the harmful substances than adults. Figure 7 shows the locations of fire stations, medical facilities, and schools in Lancaster County.

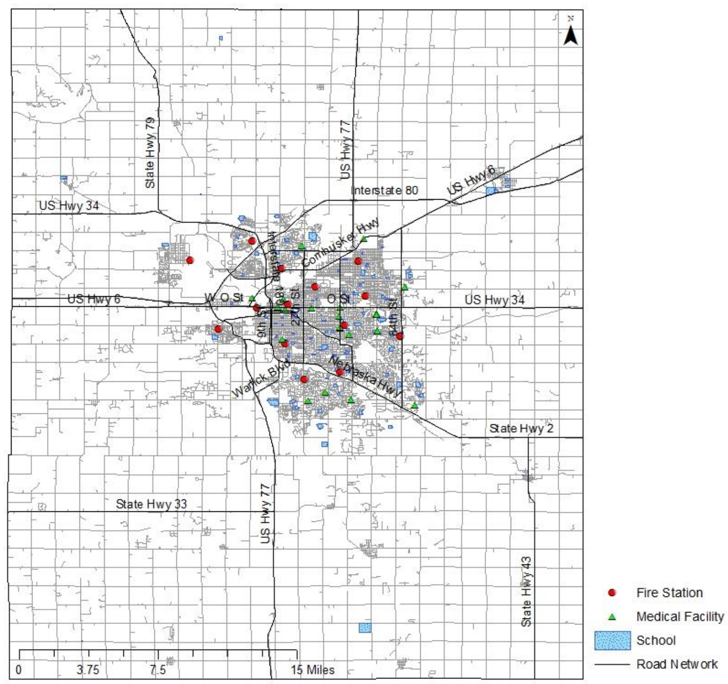

Figure 7 Locations of Fire Stations, medical facilities and Schools in Lancaster County (Fire Stations in circles, medical facilities in triangles and schools in rectangles)

3.5 Heavy Vehicle Accident Data

Analyzing historic vehicle accident data provides information about where the potential accidents could occur. If frequent accidents have occurred in a certain area then it needs to be investigated for potential future accidents. For this research, accident data were utilized to identify risk-prone roadway segments for hazmat truck accidents. The dataset was obtained from NDOR and covered a four-year (2008 to 2011) period. The data included information on the geographic coordinates of each accident, severity levels, time of day, weather conditions, etc. Usually, vehicles transporting hazmat are large-sized trucks. Therefore, only accidents involving trucks were considered in the assessment of potential for hazmat accidents. During the four-year period, there were 7,748 accidents involving trucks in Nebraska of which 947 were reported in Lancaster County. The data were used to predict sites where accident risk was high by analyzing a point density map. Figure 8 shows the 947 truck accident points in Lancaster County.

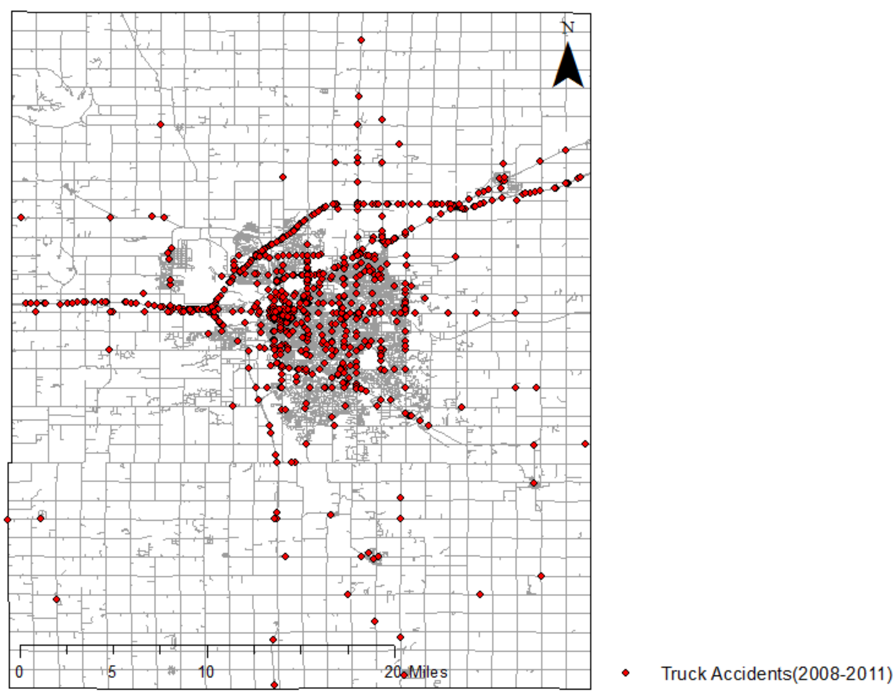

Figure 8 Truck Accident Points in Lancaster County (2008-2011)

3.6 Lancaster County Population Data

It was noted that hazmat accidents in populated areas will do more harm compared to less populated areas. This is because the total risk from hazmat movement is the product of the number of shipments, the probability of a release accident for a single shipment, and the total number of persons that may be affected by a release accident. The population data were obtained in the TIGER/Line Shapefiles from the United States Census Bureau. This dataset includes the population and housing unit count by census block from the 2010 Census for 50 states and the District of Columbia. Figure 9 shows the 2010 housing units in Lancaster County, Nebraska. The red colors represent a higher number of housing units and have higher risk of damage in case of hazmat accidents.

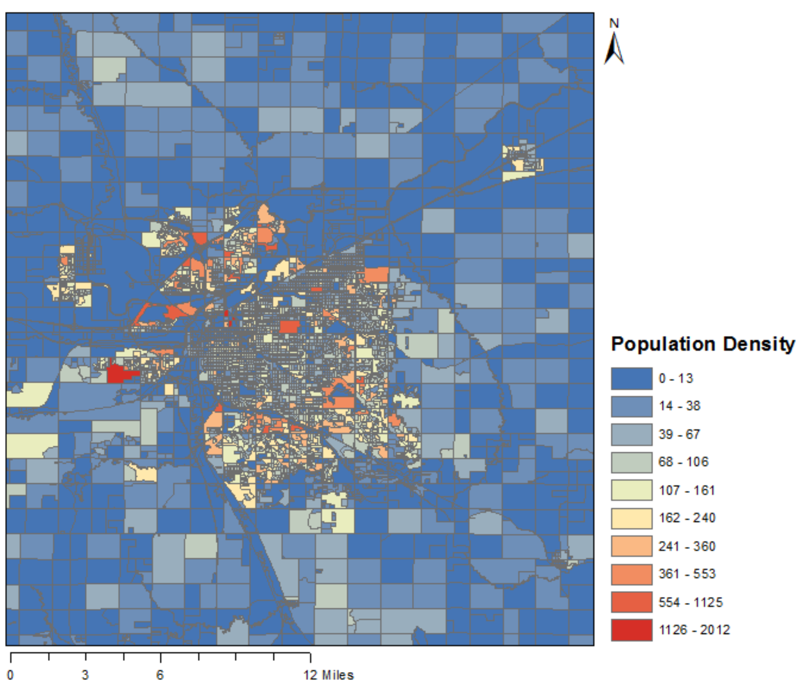

Figure 9 Housing Units in Lancaster County (2010)

4 DATA ANALYSIS

The data analysis followed the three steps shown in Figure 10. First, a spatial statistical analysis for historical truck accident data was undertaken. Accident data during the four-year period were used to find their spatial distribution in the study area, and an accident density map was obtained. Second, a GIS technique called suitability analysis was conducted to solve a multi-criteria problem. During this step, the geographic areas that satisfied different criteria were identified and considered as vulnerable areas. The identified areas were used to designate risk-prone routes in the study area. Third, the Areal Locations of Hazardous Atmospheres (ALOHA) model was used to estimate the affected area and population by a potential hazmat truck accident on the identified vulnerable routes.

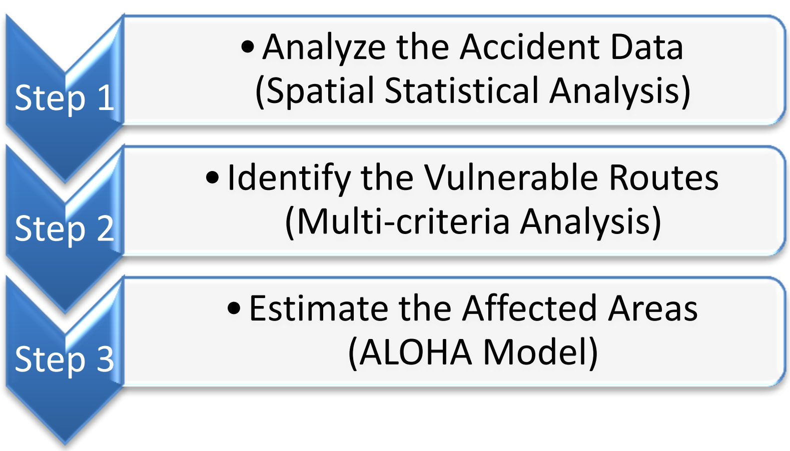

Figure 10 Steps in Data Analysis

4.1 Truck Accident Data Analysis

4.1.1 General description

Truck accident data were utilized to predict routes with potential for hazmat accidents in the study area. Analyzing spatial patterns of accidents provides information on where the accidents could be concentrated. If the distribution of accident points in a certain area is significantly different from the pattern of the same number of randomly distributed points, the point pattern may suggest clusters or dispersions, and clusters of accidents could indicate risk-prone roadway segments for truck traffic.

In traditional spatial statistical approaches for a planar area, the null hypothesis is complete spatial randomness (CSR). Its rejection represents that the points are either clustered or regularly dispersed. However, since traffic accidents are concentrated along roads, the traditional CSR hypothesis is invariably rejected. Therefore, a simple cluster analysis is not practical with respect to traffic accident point data. However, accident points can be dealt with their properties, or attribute values. In terms of the accident data obtained from NDOR, each accident contained information on injury severity levels. This severity level is measured on six different levels. Table 6 represents the description of each severity level. For instance, if high severity accidents are found to be clustered in a certain area, the location would be considered as a high severity accident-prone area. If low severity accidents are gathered together in another area, that can be regarded as a low severity accident-prone area. Using the attribute values of accidents, clusters having high or low severity accidents were identified.

In the original accident data, severity levels were classified as FATAL, INJ-A, INJ-B, INJ-C, PDO and N-R (not reported). For each severity level, corresponding values in numbers were added because the spatial analysis uses attribute values in numbers. That is, FATAL accidents have the highest number (6), and the number goes down as the severity level reduces. With these attribute values, the spatial analytic concepts of Global Moran's I, Getis-Ord Gi* statistic, and Kernel Density were used to discover where the high or low severity accidents were clustered and how dense those accidents points were in the study area.

Table 6 Accident Severity Levels

Type	Description	Value
FATAL	Fatal crashes	6
INJ-A	Severe injury crashes	5
INJ-B	Moderate injury crashes	4
INJ-C	Minor injury crashes	3
PDO	Property damage only crashes (Damage crashes of $1,000 or more)	2
N-R	Non-reportable (Damages less than $1,000)	1

4.1.2 Global Moran's I

Global Moran's I is a spatial autocorrelation tool to identify if the spatial pattern of attribute values in the study area is clustered, dispersed, or random (Moran, 1950). As the name suggests, Global Moran's I searches for spatial patterns of feature values for the whole study area. It is unable to pinpoint where the high or low attribute values are clustered locally. Instead, it only provides whether the whole study area is clustered with high attribute values and/or low attribute values with statistical significance. The technique produces the Moran's I Index value to show the results. Also, z-score and p-value are determined to show the significance of the calculated index. The index and the z-score can be computed by the following equations:

$$\mathrm{I} = \frac{n}{\sum_{i=1}^{n}\sum_{i=1}^{n} w_{i,j}} \times \frac{\sum_{i=1}^{n}\sum_{i=1}^{n} w_{i,j}(x_i - \bar{X})(x_j - \bar{X})}{\sum_{i=1}^{n}(x_i - \bar{X})^2}$$

$$z\ score = \frac{I - E[I]}{\sqrt{V[I]}}$$

Where, x_i is an attribute value of a target point, x_j is an attribute value of a neighboring point, w_{ij} is the spatial weight between point i and j for example, as $w_{ij} = 1$ if $i \neq j$ and the two points are within the specified distance, and by $w_{ij} = 0$ otherwise, n is the total number of points.

The expected value and the variance of Moran's I are given in the following equations:

$$E[I] = -1/(n-1)$$

$$V[I] = E[I^2] - E[I]^2$$

The ranges of Moran's I index are between -1 and 1. A positive value represents distribution of high and/or low attribute values that are clustered in proximity, while negative value indicates the distribution of high and low attribute values that are dispersed compared to the random distribution. A zero value implies no spatial autocorrelation amongst the points, representing the distribution of attribute values are randomly distributed.

When it comes to statistical hypothesis in Moran's I, the null hypothesis is that the attribute values for each point are randomly distributed among the points without changing the location of the points. If the p-value is not statistically significant, the null hypothesis cannot be rejected, concluding that the study area has randomly distributed attribute values. If the p-value is statistically significant, the sign of the z-score determines whether high and low attribute values are clustered or dispersed. A positive z-score means the study area has high and/or low attribute values aggregated, while a negative z-score represents that high and/or low attribute values are dispersed.

In this research, straight line distances among accident points were considered to define clusters, and a fixed distance band was used for the spatial conceptualization. To be specific, if a certain fixed distance is set, GIS calculates the target point with its neighboring points within that threshold distance. The points beyond the distance are excluded from calculations. The Global Moran's I spatial autocorrelation tool was used to identify proper critical distance to calculate neighboring points used in the hot spot analysis. That is, it helps discern a critical distance, which makes the spatial autocorrelation stronger. This is because using different critical distances produces different z-scores and if an analysis with a certain distance produced the peaked z-score in the series of Global Moran's I analysis, the selected distance is the search scale radius, which makes the spatial clustering the strongest.

By changing the distance, multiple trials of Moran's I were conducted using an incremental spatial autocorrelation tool. This measures how the degree of spatial autocorrelation changes as the distance changes using Global Moran's I, and the degree can be measured by z-score. The initial distance was set to 328.08 feet (100 meters), and the increment was 164.04 feet (50 meters). A total of 30 distance bands (100m ~ 1550m) were tested to find the peaked z-score. Figure 11 shows the z-scores at different distances for truck accident points in Lancaster County. The detailed information about the result of Incremental Spatial Autocorrelation in 30 different distance bands is provided in Appendix B. The peaked z-score is highest at the distance of 1,804.46 feet (550 meters) for the critical distance. The z-score and p-value were 2.804 and 0.00504 respectively. Thus 1804.46 feet (550 meters) was used in the hot spot analysis for the search radius to define neighboring points.

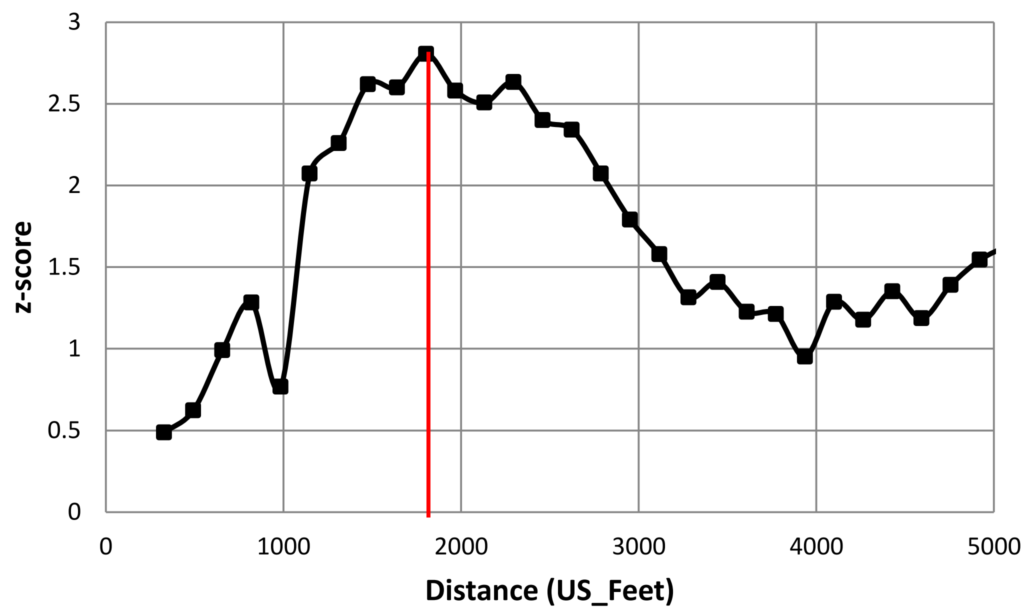

Figure 11 Spatial Autocorrelation by Distance for Truck Accidents in Lancaster County

4.1.3 Hot Spot Analysis (Getis-Ord Gi* Statistic)

The hot spot analysis was used to find clusters with high or low feature values with statistical significance. Hot spots refer to clusters with high attribute values while a cold spot represents clusters consisting of low feature values. For each target point, the analysis searches adjacent points within the critical distance band. Afterwards, the analysis determines whether the target point is surrounded by high or low feature values with statistically significant levels. Instead of global spatial statistics such as Global Moran's I, the hot spot analysis uses the Getis-Ord Gi* Statistic, which is a local variation measure of spatial clustering. That is, the analysis can help pinpoint those clusters. If a target point containing a high attribute value is surrounded by enough neighboring points with high attribute values, the point is determined to be a statistically significant hot spot. In this research, a hot spot analysis was conducted to find where the high and low severity accidents were clustered. The clustering locations could be considered high or low severity accident-prone areas.

The calculation of the Getis-Ord Gi* statistic is given as the following equation. The Gi* statistic itself is the z-score. If the z-score is not statistically significant, the target point is surrounded by high and low feature values together, resulting in no clustering of high or low feature values. When the z-score of a target point is statistically significant, it can either be clusters of high or low values. A positive z-score means high feature values are clustered (hot spots), while a negative z-score represents low feature values clusters (cold spots). In terms of the size of z-score, a larger z-score indicates a higher degree of clustering while a smaller z-score implies a lower degree of clustering.

$$Gi^* = \frac{\sum_{j=1}^{n} w_{ij}x_j - \left(\frac{\sum_{j=1}^{n} x_j}{n}\right) \times \sum_{j=1}^{n} w_{ij}}{\sqrt{\frac{\sum_{j=1}^{n} x_j^2 - \sum_{j=1}^{n} x_j}{n}} \times \sqrt{\frac{n\sum_{j=1}^{n} w_{ij}^2 - \left(\sum_{j=1}^{n} w_{ij}\right)^2}{n-1}}}$$

Where, x_i is an attribute value of a target point, x_j is an attribute value of a neighboring point, w_{ij} is the spatial weight between point i and j for example, as $w_{ij} = 1$ if $i \neq j$ and the two points are within the specified distance, and by $w_{ij} = 0$ otherwise, n is the total number of points.

Hot spot analysis was conducted in GIS with the truck accident data. The specified critical distance band was set at 550m (1804.46 feet), which made spatial autocorrelation stronger. That is, the spatial weight (w_{ij}) was equal to zero beyond that distance since the fixed distance method was chosen in the analysis. Figure 12 shows the result of Hot Spot Analysis.

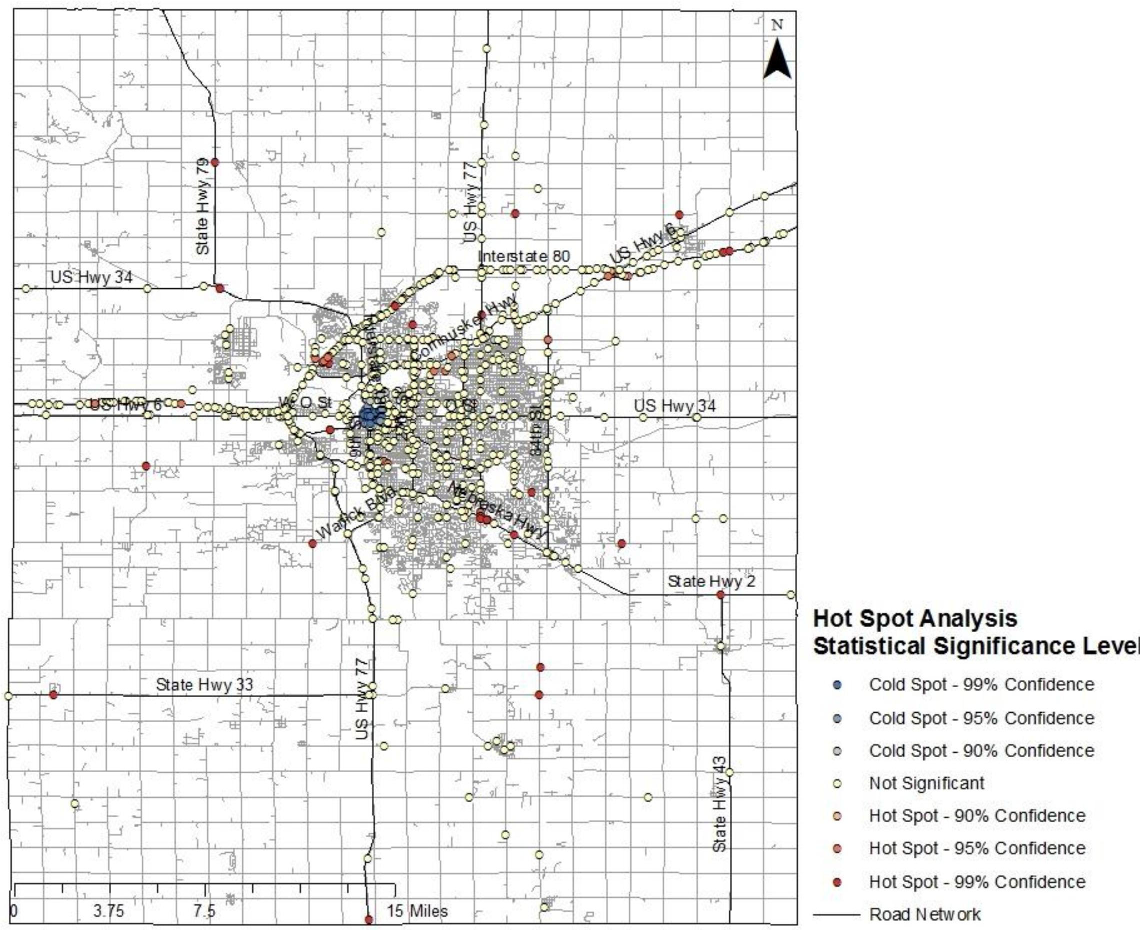

Figure 12 Hot Spot Analysis for Truck Accidents in Lancaster County

The result of the hot spot analysis showed the points with statistically significant levels. In the downtown area of Lancaster County substantial cold spots, or clusters of low severity accidents, were detected. Figure 13 shows the clusters of low severity accidents near the downtown area. Most of the cold spots were at the intersection of West O Street and 9th Street. Even though many accidents occurred at that location, the severity level for the cluster was somewhat mild since the area has a complex road network, making traffic move slowly. Several hot spot clusters were identified across the study area. Hot spots tended to be located on high speed roadways such as interstate highways or major highways. Also, they were usually near intersecting or merging points of more than two roadway segments.

Figure 13 Clustering of Low Severity Accidents

4.1.4 Accident Density

To consider the clustered truck accident points objectively in the analysis, a density map for each point was produced. In GIS, the Kernel Density tool estimates a magnitude per unit area from accident points using the Kernel function. This creates smooth contour lines from the center in which a point exists to the reference location. With other points, the density map can be created with smoothly curved surfaces for each truck accident point.

Instead of applying accidents equally to get an accident density map, a different weight for each accident was applied in terms of the results of the hot spot analysis. The hot spot analysis produced z-scores on the accidents to decide which belonged to a hot spot or cold spot with confidence levels. Thus, a different weight was applied to each accident using its respective z-score. For instance, accidents with z-scores greater than 2.54 were given the highest weight (7) since the points were regarded as hot spots at a 99% confidence level. Accidents with z-scores larger than 1.96 and smaller than 2.54 were given the second highest weight (6) since the points were identified as hot spots at a 95% confidence level. In a similar manner, hot spot accidents with a 90% confidence level were weighed at 5. Statistically not significant accidents, meaning they are not in hot spots or cold spots, were designated as 4 in weight. Cold spot accidents with a 90% confidence level were assigned a 3 in weight since the chance of having high severity clustered accidents is lowered as the confidence level increases in cold spots. Thus, accidents having 95% and 99% levels of confidence for cold spots became 2 and 1 for the weight respectively. Table 7 shows the accident weight classifications in terms of z-scores and confidence levels. GIS calculates the point density map using the weights specified with z-scores in the Hot Spot Analysis. That is, the point density is formed with the number of points as well as the weight of each point. The weight here is z-scores and confidence levels. The higher the possibility of being a hot spot, the heavier the weight is for each accident point.

Table 7 Accident Weigh Classifications

Class	Z-score range	Confidence level	Weights
Hot Spot	$z \geq 2.54$	99%	7
	$1.96 \leq z < 2.54$	95%	6
	$1.645 \leq z < 1.96$	90%	5
Insignificant	$-1.645 < z < 1.645$	Not Significant	4
Cold Spot	$-1.96 < z \leq -1.645$	90%	3
	$-2.54 < z \leq -1.96$	95%	2
	$z \leq -2.54$	99%	1

Figure 14 shows the Kernel Density map in the center of Lancaster County. The search radius for Kernel Density was set to 1804.46 feet (550 meters) because the distance was found in the multiple trials of Global Moran's I to be the maximum spatial autocorrelation among points. Smoothly tapered surface areas were developed to each point and the density value of the surface areas decreases when the distance increases from the point. In the density map, the identified hot spots were appropriately reflected by considering z-scores as weights. Despite the significant number of low severity accidents clustered in the downtown area, the map with weights produced a balanced density map by focusing more on hot spots, or aggregated severe truck accidents. This was because the density map used not only the number of points, but also the weights for the z-scores.

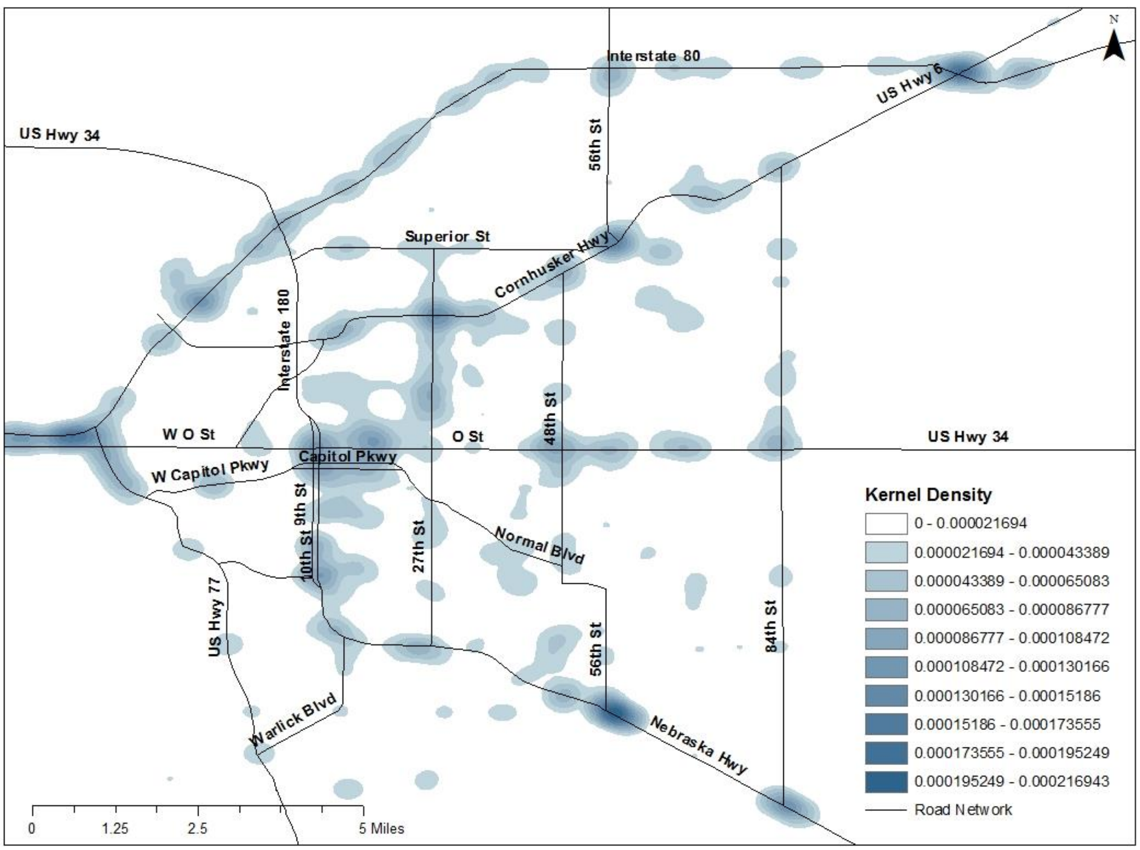

Figure 14 Kernel Density Map in the Center of Lancaster County

4.2 Multi-criteria Analysis

Compared to selecting a risk-prone area with only one criterion, analyses considering diverse criteria may produce a more accurate and reliable result. In this research, several different layers, such as AADT; wind speed; the locations of hazmat facilities, fire stations, medical facilities and schools; heavy vehicle accident density; and population density were integrated and scrutinized to locate areas most susceptible to a hazmat accident.

In order for the different input layers to be integrated into one result layer, all the input layers were converted into raster format. That is, each layer was defined as a space where equally-sized cells are posed in a grid structure form of rows and columns. Figure 15 shows a common 10×10 raster structure.

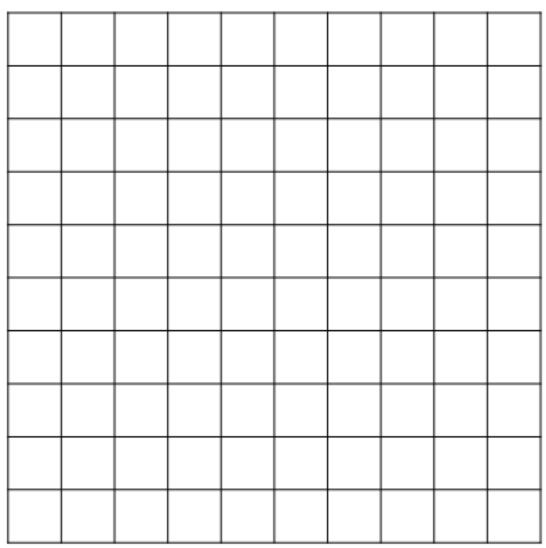

Figure 15 Raster Data Structure

Since each cell in a raster has its own value, more than two raster datasets can be combined by adding, averaging, or using other techniques for these values, creating a resulting raster form where the values in the cells are arranged according to the operation used on the integrated layers. However, when considering more than two layers together, the numbering system from input layers may be different. For instance, in this research, the wind speed map had a numbering system for speed (m/s or ft/s) while the population density was measured using housing units (number of houses). The range value for each different input raster layer must be identical, which can be achieved by reclassifying each raster datum. Once the range values for different layers are comparable, the layers can be combined by adding or averaging the cells based on geographic overlap. Figure 16 shows the simple averaging combination process of two different layers. By averaging the values in the cells, the most suitable area in terms of different criteria can be detected.

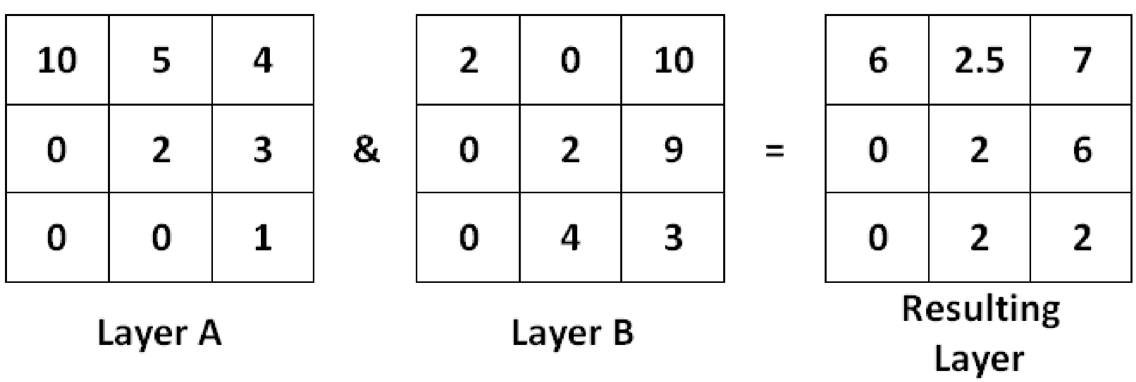

Figure 16 Averaging two Different Layers

When joining different raster datasets, it may be that one raster data is deemed more important than another. That is, input layers may be considered with different risk significance. For instance, in this research, roadway segments that have higher AADT should be considered more vulnerable than those having lower AADT. Thus, different weighting schemes should be applied for different raster layers. Figure 17 shows an example applied with weights (30 percent for layer A and 70 percent for layer B). In such a case, layer B is considered more significant and the resulting layer shows different arrangement of cell values compared to the one in Figure 16.

3	1.5	1.2
0	0.6	0.9
0	0	0.3

Layer A × 0.3

+

1.4	0	7
0	1.4	6.3
0	2.8	2.1

Layer B × 0.7

=

4.4	1.5	8.2
0	2	7.2
0	2.8	2.4

Resulting Layer

Figure 17 Combining Two Different Layers with Weighing

Using the weighted overlay function in ArcGIS, different datasets can be integrated with weighted values. The system indicates the calculated cell values in a different color scheme to show where high or low values are for appropriateness of a given study area. The technique was considered useful to deal with multi-criteria problems. In this research, different properties of the diverse data obtained to identify vulnerable areas in terms of a potential hazmat truck accident were investigated with this technique. Figure 18 represents the flowchart of the multi-criteria analysis.

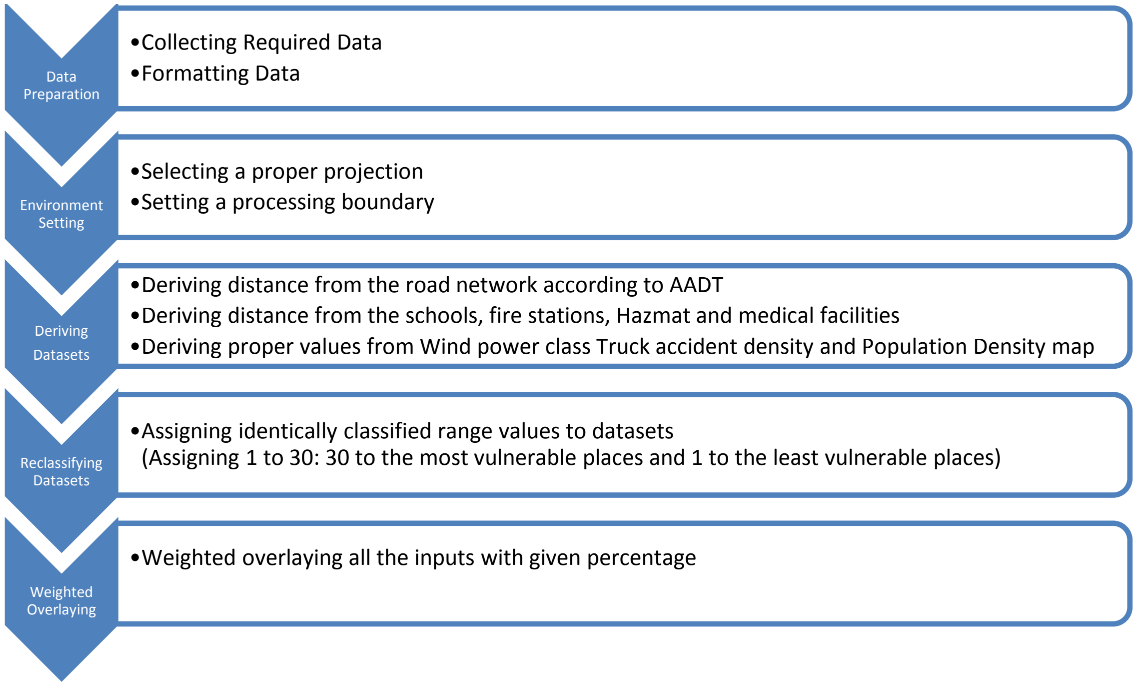

Figure 18 Flowchart of Multi-Criteria Analysis

4.2.1 Data Preparation

The data were obtained from diverse sources and explained in section 5.1. The raw data of the locations for fire stations, medical facilities, hazmat facilities, and schools were available in an Excel spread sheet containing information on coordinates of those facilities. These facilities were geocoded and created in the Shapefile format in GIS with visual representations on a map. The road network was classified into three different groups representing different AADT (0~15,000; 15,001~30,000; and 30,001 or more). This is because AADT was considered an indicator of the degree of potential danger for hazmat truck accidents. Thus, the three roadway groups with different AADT were loaded in three layers. Also, wind speed, population, and truck accident density layers were added in GIS. The truck accident density layer was the output of accident data analysis explained in the section 4.1. Finally, all the layers were clipped to fit to the Lancaster County area only. That is, in using the Lancaster County layer, all the areas beyond the County boundary were excluded in this analysis.

4.2.2 Environment Setting

Before the analysis, a map projection and a calculation processing extent needed to be set in ArcGIS. The map projection transforms the curved surface of Earth to a flat surface. In the course of this process, some distortion is inevitable since the flat surface cannot perfectly mirror the spherical surfaces of Earth. There are many projections available that have their own mathematical transformation processes to convert the Earth's surface into a map on a flat piece of paper by preserving information such as distance, area, or direction. This research used the Equidistant Conic method, which is a projection method by which distances among features along the meridians are preserved proportionately. Application of the Equidistant Conic projection method helped produce more appropriate results since this research was mostly based on the distances among and from point data. Also, an output processing extent was also set that allowed calculation processes in ArcGIS to continue until the set boundaries were reached. The analysis boundary was defined to be the study area as Lancaster County.

4.2.3 Deriving Raster Datasets

The feature class datasets such as polygon, line, or point must be converted into the raster datasets in multi-criteria analysis. The data for the location of fire stations, schools, hazmat facilities, and medical centers were converted into the raster data format using the Euclidean distance tool. This calculates distances from the features and assigns corresponding values to the cells in a raster data form. For example, when the locations of hazmat facilities were considered, the raster cell values decrease as the distance from each facility increases in straight lines. In a similar way, line feature class datasets for roadway groups with different AADT were converted into the raster data form. The distance was calculated from each line feature and cell values were arranged with the distance.

The polygon feature class datasets, such as population density and wind speed class, already had assigned values in each polygon feature across the map. Thus, these datasets were converted into the cell-based raster format by maintaining the values. Since a cell may include more than one polygon feature value, it is required to manage how the cells will be assigned with multiple feature values included in one cell. Three different methods exist to determine polygon values in a cell-based raster format. The first method is to use the cell center with which GIS assigns a value in a cell for the raster form by considering where the center of the cell is located. If the center meets with a certain polygon feature value, the value becomes the cell value. The second method is to use the maximum area included in a specified cell. In a cell, the biggest polygon area and its value represent the cell. The last method is to use the maximum combined area where cell values are determined with the combined majority polygon features within the cells. This method is distinguished from the maximum area method because it determines one majority area by aggregating homogeneous fragmented polygons within a cell. Figure 19 shows the illustration of how the cell value is determined with multiple polygon feature values assigned in one cell.

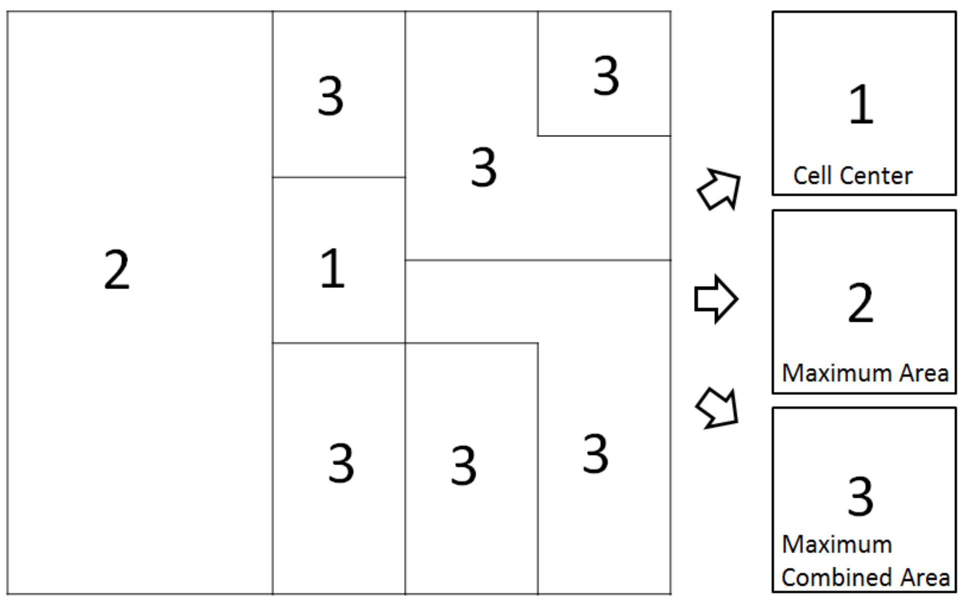

Figure 19 Illustration of an assigned value in a cell in raster datasets

With the datasets used in this analysis, all three methods produced a fairly similar result. This is because the specified cell size in this research was significantly small and this small cell size formed a considerably detailed resolution across the study area. Thus, the result of three were the almost same and the cell center method and its result map were used for the analysis. Meanwhile, the truck accident density map obtained in the accident data analysis was originally produced in a raster data format. Thus, it did not require the transformation and was used directly. Figure 20 shows all the derived raster datasets.

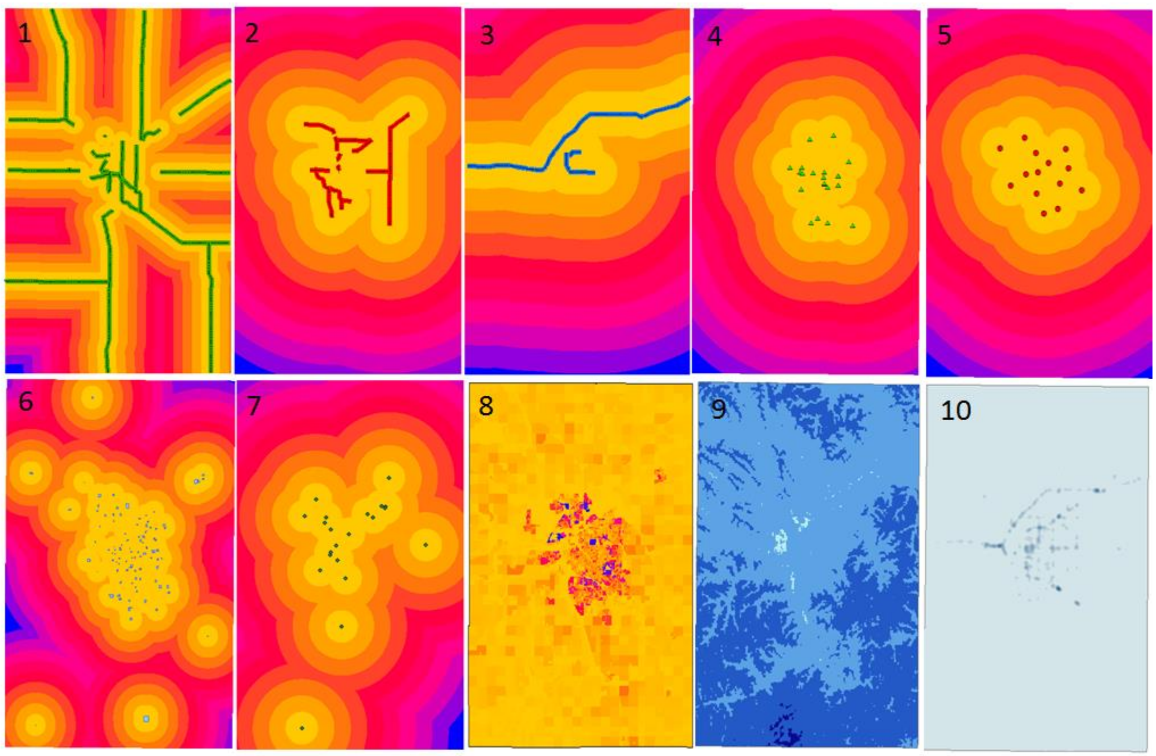

Figure 20 Derived Datasets

(1: Roadway segment AADT (0 to 15000), 2: Roadway segment AADT (15001 to 30000), 3: Roadway segment AADT (30001 or more), 4: Medical Facilities, 5: Fire Stations, 6: Schools, 7: Hazmat facilities, 8: Population Density (Housing Units), 9: Wind Speed Class Map, 10: Truck Accident Density)

4.2.4 Reclassifying Datasets

To integrate different raster datasets into a single dataset, all the input rasters needed to be set in a common range scale. Since the datasets derived from the previous step had their own values in different measurement units, all the input datasets were reclassified from 1 being the least vulnerable to 30 being the most vulnerable in terms of hazmat release accidents on roads. That is, the surfaces on input raster datasets were equally divided into 30 different segments. Each segment represents a different risk level. Figure 21 shows the reclassified datasets.

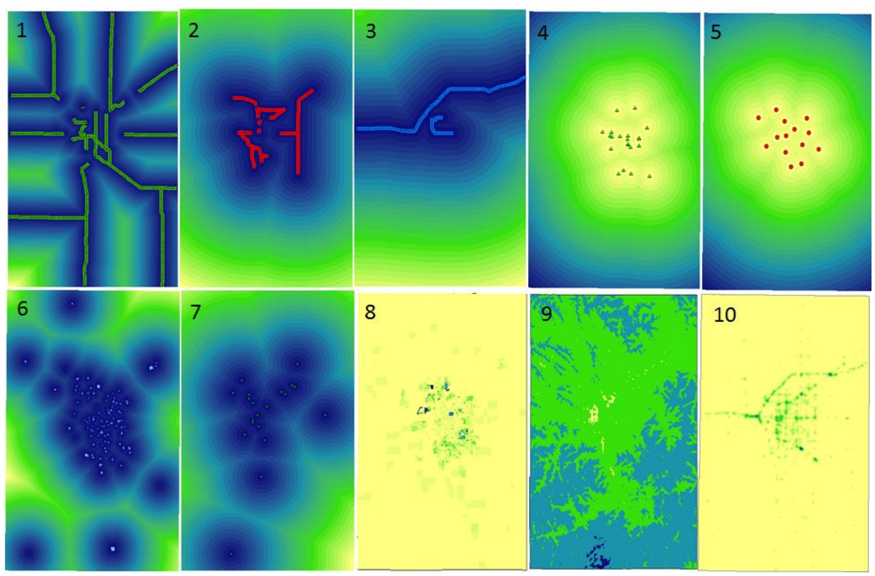

Figure 21 Reclassified Datasets

(1: Roadway segment AADT (0 to 15000), 2: Roadway segment AADT (15001 to 30000), 3: Roadway segment AADT (30001 or more), 4: Medical Facilities, 5: Fire Stations, 6: School, 7: Hazmat facilities, 8: Population Density (Housing Units), 9: Wind Speed Class Map, 10: Truck Accident Density)

4.2.5 Weighting and Combining

To obtain the integrated result raster layer, the reclassified datasets were overlaid in GIS to find the most vulnerable place. When combining the datasets, it is realistic to assign a different weight to each raster dataset according to the relative importance of the layer. In this analysis, equal weights were assigned except for the roadway groups that had different AADT. Table 8 shows the weighting scheme applied for this analysis.

Table 8: Percentages of Influence for Each Raster Datum

Raster Datasets		Influence (%)
Roadways	AADT(0 to 15,000)	5
	AADT(15,000 to 30,000)	10
	AADT(30,000 or more)	15
Hazmat Facilities		10
Medical Centers		10
Fire Stations		10
Schools		10
Wind Speed		10
Truck Accident Density		10
Housing Unit		10

Except in the case of roadway groups, 10% of weight was used for all other raster datasets. In this analysis, the weighting scheme applying different weights on the different raster layers was not used due to the lack of information and literatures which specify relative importance among different raster layers. Instead, this research more focused on developing procedures to be applied later with different analysts who use their own local factors determining relative importance of input layers. All things considered, the final result map is shown in Figure 22. The darker shaded areas were more vulnerable to hazmat accidents.

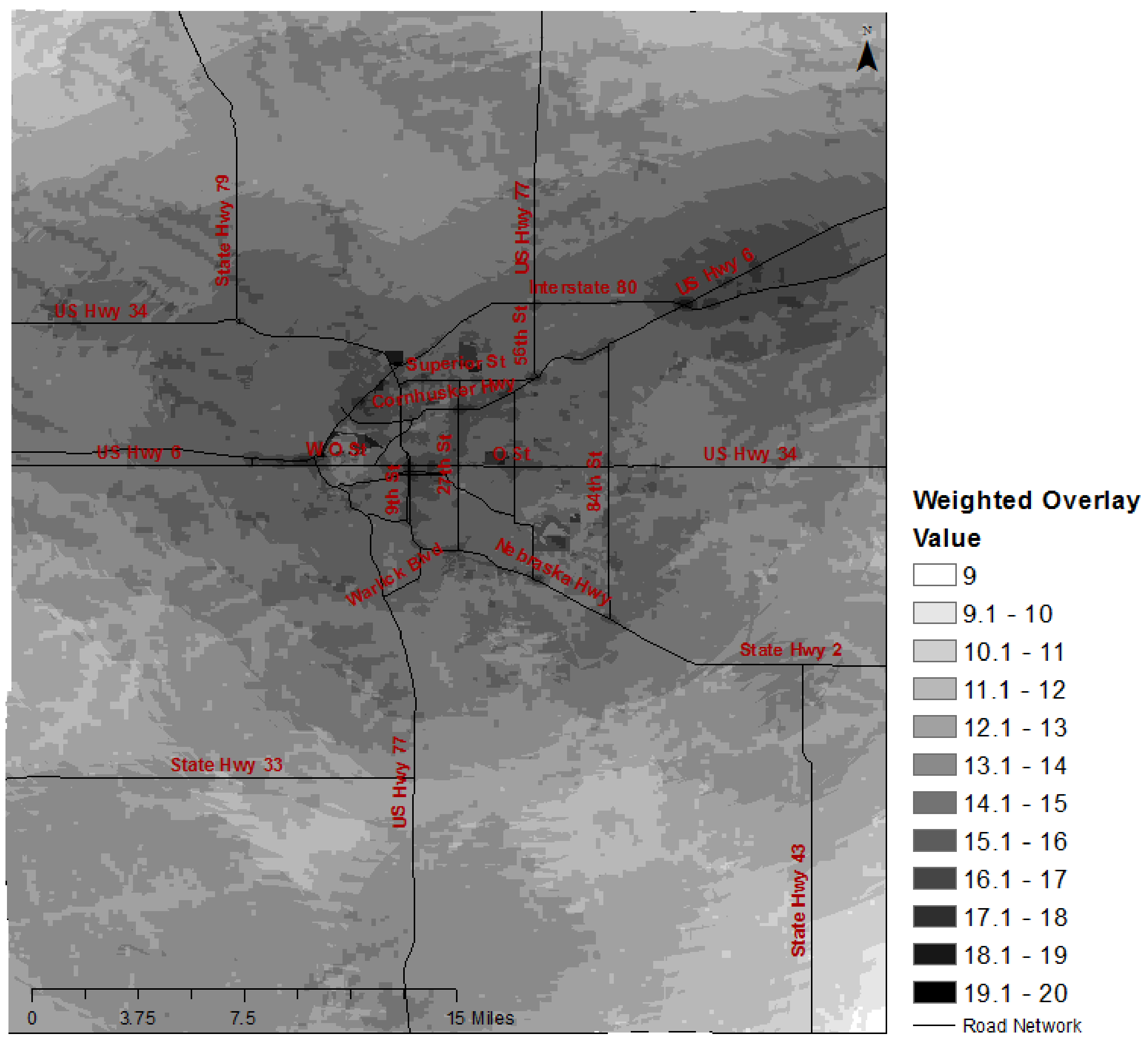

Figure 22 Integrated Result Raster Layer for Hazmat Truck Accidents

4.2.6 Identifying Risk-Prone Roadway Segments

The integrated result map from multi-criteria analysis was used to identify risk-prone routes in Lancaster County. The weighted value range was between 9 and 20, and the top two tiers (19 and 20) were considered to be the first prioritized risky areas with respect to hazmat truck accidents. Figure 23 shows the highlighted top two tiers. That is, if the routes are near those highlighted yellow areas, they are considered high-risk with respect to the hazmat truck accidents.

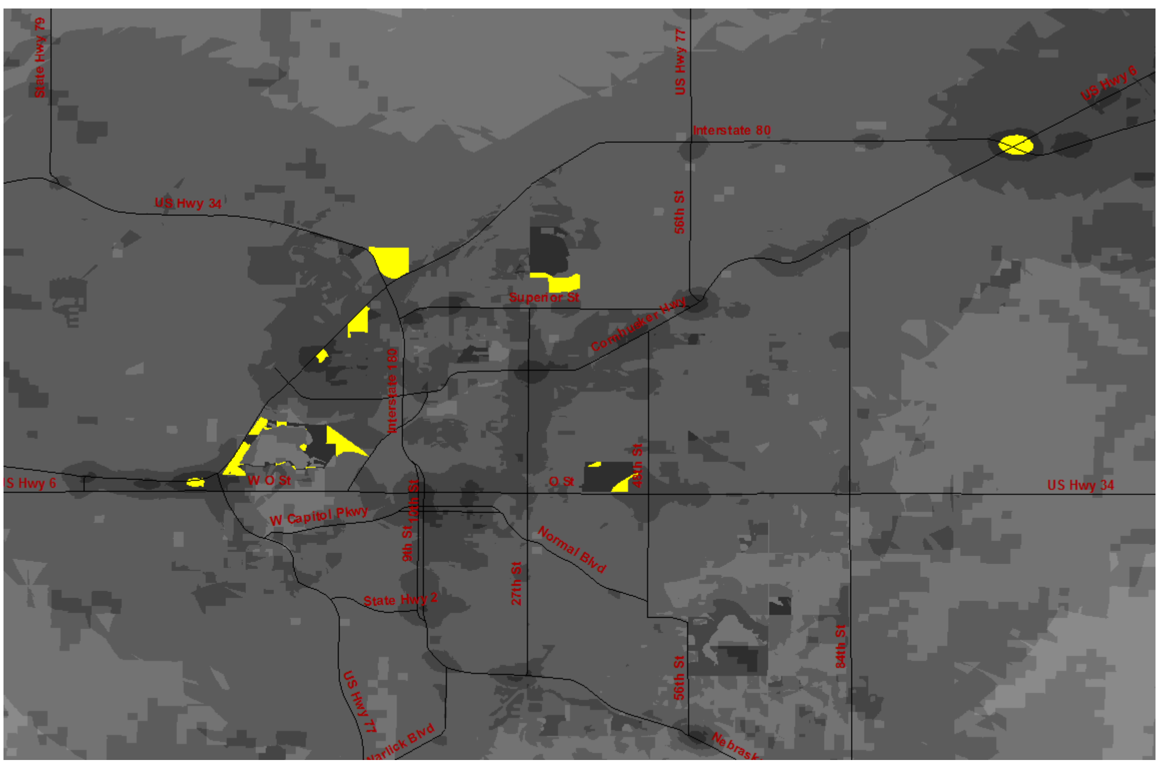

Figure 23 Highlighted Top Two Tiers in MCA

A 300-ft wide buffer was created for each highlighted area to select nearby risk-prone routes. The buffers for these areas also combined tiny fragmented roadway segments in reasonable length. Figure 24 shows the selected routes. The routes were overlapped with the risk-prone areas.

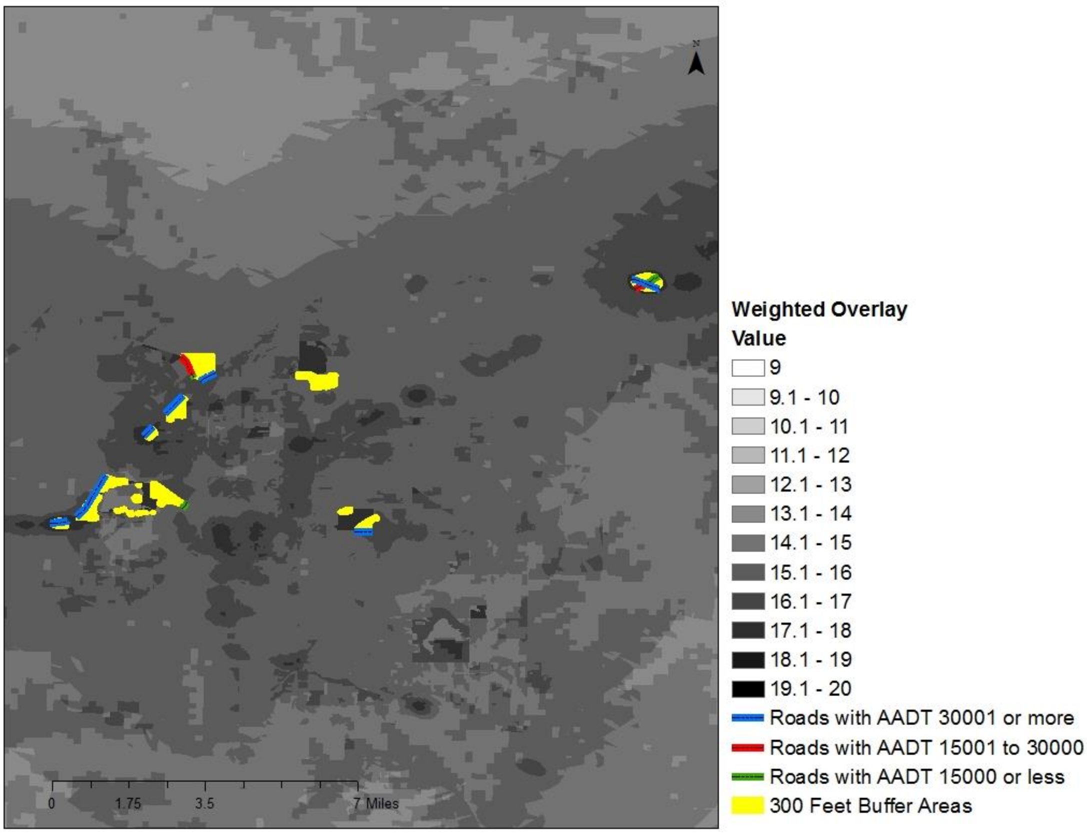

Figure 24 Identified Vulnerable Routes in Lancaster County

4.3 Impact Analysis

With the identified vulnerable roadway segments, impact analysis was conducted to estimate the affected areas and quantify the population vulnerable to potential hazmat truck accidents. The analysis was explained with a theoretical scenario where a truck trailer carrying chlorine had overturned on a risk-prone route identified by the multi-criteria analysis. Using hazmat release pattern modeling software called Areal Locations of Hazardous Atmospheres (ALOHA), diffusing patterns of hazamt from the accident point were portrayed. With the specified disperse patterns and distances of the hazmat release, generalized affected areas were estimated, and housing units within the identified patterns were considered as affected population.

4.3.1 Areal Locations of Hazardous Atmospheres (ALOHA)

ALOHA is computer software that models hazardous material release patterns. It was developed by the National Oceanic and Atmospheric Administration (NOAA) and the US EPA, and is distributed by the National Safety Council (NSC). This program has been used as an emergency response tool for hazmat release accidents because it can predict the air dispersion of toxic materials. Once several factors about the hazmat accident are determined, the program delineates atmospheric conditions from toxic source materials based on the user-specified Level of Concern (LOC). LOC in this research is a critical level of toxicity set to create different threat zones. The software allows setting three LOCs and estimates threat zone boundaries accordingly. Emergency

Response Planning Guidelines (ERPG) were used for the toxic LOCs for chlorine, so the three defined LOCs were 20 ppm, 3 ppm and 1 ppm, respectively, in chemical concentration. That means the program calculated the different toxic zone boundaries according to the chemical concentration value.

The derived atmospheric patterns for hazmat release were utilized to estimate and quantify the affected areas and population in Lancaster County. Figure 25 shows an example of the model estimation for a chlorine release accident with three different threat zones based on the specified levels of toxicity. The smallest ellipse is the zone where the chemical is highly concentrated. Larger ellipses indicated lower concentrations of toxicity levels due to wind dispersal. The software considers statistical uncertainties about wind direction. The areas drawn with lines beyond the shaded areas are probable threat zones at a 95% confidence level according to wind direction uncertainty. This means that the model results have a range of variability. As an example scenario with several assumptions, a plausible hazmat release pattern is estimated in the following section.

Figure 25 ALOHA Model Prediction in Lancaster County with Three different Threat Zones

4.3.2 A Virtual Scenario for ALOHA Modeling

A virtual scenario for a hazmat release accident was used to model an example case, and it reads as follows: On July 19, 2014, at 10:03 a.m. local time, a truck trailer carrying chlorine was overturned on the Interstate Highway 80 near Superior Street in Lancaster County. The truck had a horizontal cylinder tank whose diameter was 4 feet and length was 36 feet. It included 3,046 gallons of chlorine liquid (90% of a full tank). When trying to avoid a sedan changing lanes, the truck overturned and the tank developed a hole resulting in about 17% of the liquid chlorine leaking on to the paved roadway and gasified into surroundings. The leak was about a 2-inch circular hole, situated 3.3 feet from the concrete bottom. The outside temperature at the site was 75°F, and the wind speed was 6.15 miles per hour (measured at 160.04 feet from the ground) from northwest. It was partly cloudy and about 75% humidity. The terrain on the site was open without any buildings.

To model the hazmat release accident, several input data were required in the program including crash site data, chemical data, atmospheric conditions, and chemical source data. First, the information on the location, date, time, and surrounding environment of the accident point were input. Second, the chemical type was chosen from the provided library function in the program. Third, atmospheric conditions such as wind speed and direction, air temperature, cloud cover, and humidity were selected. Finally, chemical source information on tank size, tank types, stored chemical temperature, and types of leaking were included. Table 9 shows the input data for ALOHA modeling.

Table 9 ALOHA Model Input Data

Description	Input types	Input
Site-specific data	Location	Lincoln, Nebraska
	Time	July 19, 2014, at 10:03 a.m. local time
Chemical data	Chemical name	Chlorine
Atmospheric conditions	Wind	6.15 miles per hour from NW at 164.04 feet
	Ground roughness	Open country
	Cloud cover	Partly cloudy
	Air temperature	75°F

	Relative humidity	75%
Chemical source	Tank diameter	4 feet
	Tank length	36 feet
	Liquid volume	3,046 gallons (90% of full tank)
	State of the chemical	Liquid inside the tank/Gas outside
	Stored temperature	-30°F
	Opening type	Circular opening with 2 inch diameter
	Released quantity	17% of 3,046 gallons

Figure 26 shows the estimated footprints, or toxic threat zones, for the hazmat release accident according to ERPG (20ppm, 3ppm, and 1ppm for chlorine). To be specific, the smallest areas within the red line had a chlorine concentration greater than 20 ppm. The next larger areas within the yellow line had a chlorine concentration greater than 3 ppm but less than 20 ppm. Finally, the areas within the black line represented a chemical concentration greater than 1 ppm but less than 3 ppm. The detailed ALOHA result summary table can be found in Appendix C.

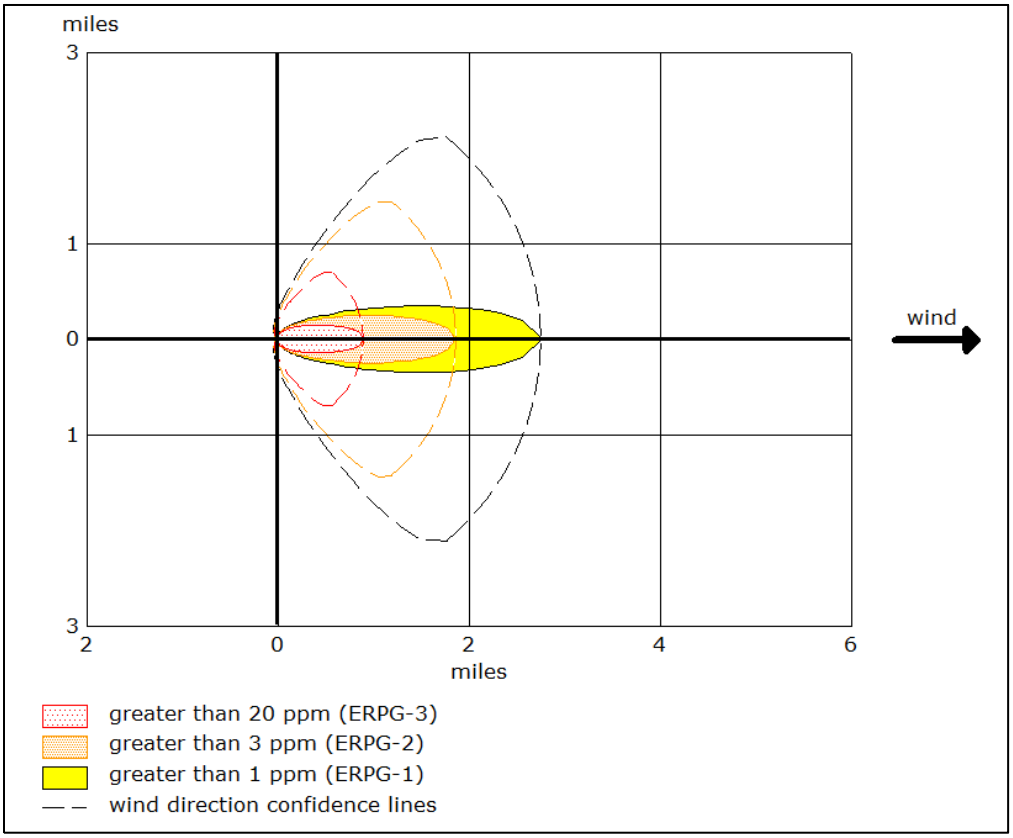

Figure 26 ALOHA Modeling for Virtual Scenario

To estimate the affected areas, the footprint was loaded in GIS using ALOHA's ArcMap import tool with appropriate coordinates. The affected areas for the chlorine release accident were portrayed from the accident spot in Lancaster County as shown in Figure 27. The calculated threat zone distances for the three chemical concentration levels were 0.9, 1.9, and 2.8 miles respectively.

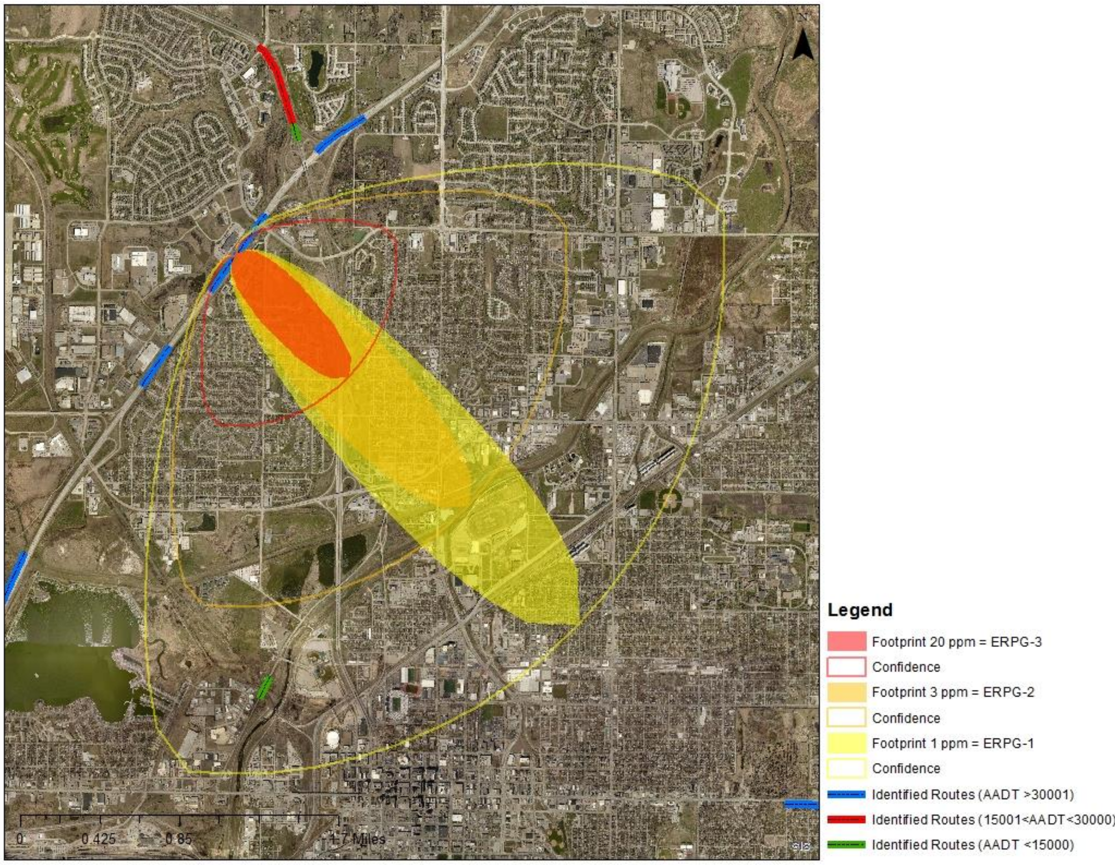

Figure 27 Chlorine Release Accident Dispersion Pattern in Lancaster County

4.3.3 Estimation of Affected Area

One of the common methods to estimate the affected area is to use a band of fixed width on a link. Calculating the number of people residing inside of the area produces the link consequence. The main assumption of this method is that people living inside of the band will be impacted equally and no one outside of the band will be impacted. However, it does not consider wind speed and direction of chemical dispersion. One circle cannot mirror different impact levels, which are based on the concentration level of toxic substances. Also, when the wind is blowing, chemical substances move and affect areas further downwind while upwind areas have less or no impact. That is, an impact analysis with circular areas may produce erroneous prediction results. Therefore, it is important to differentiate the consequences at different distances by applying concentration levels. Using ALOHA software, it was possible to use a dispersion model to estimate the concentration levels at different distances from a pollution source. It predicted three different threat zones from the most concentrated chemical area to the least concentrated area, considering the site specific data, chemical information, atmospheric conditions, source data, and other important characteristics.

To quantify the area, the estimated model in ALOHA was projected onto an aerial photo in ArcGIS, and the actual affected areas within the dispersion model were considered as affected areas. Since the model included statistical uncertainty about wind direction, both actual affected areas and total possible affected areas at a 95% confidence level were calculated. Table 10 shows the areas measured in acres. Dispersion of chemical on larger area resulted in reduced chemical concentration. However, the affected area size increased drastically as the chemical concentration attenuated from the source point.

Table 10 Measured Areas for Chlorine Dispersion Accident

Statistical Occurrence	Emergency Response Planning Guidelines (ERPG) for Chlorine Concentration		
	ERPG-3 (20 ppm)	ERPG-2 (3 ppm)	ERPG-1 (1 ppm)
Actual Affected Areas (Shaded areas)	127.27	446.95	900.39
Total Possible Affected Areas at 95% Confidence (Dashed areas)	562.72	2295.48	4935.67

Note: the unit of area is the acre.

4.3.4 Estimation of Affected Population

From the possible hazmat release plumes portrayed in GIS, people affected by the accident were estimated using 2010 population data for Lancaster County. The data were obtained from the US Census Bureau and included population and housing units by census block groups. All of the block groups within the identified hazmat release plumes were considered, and the number of people and the housing units within the blocks were counted to estimate the affected population. When selecting affected blocks, blocks within the boundaries for hazmat plumes were included. However, for the blocks that were partially included within the boundary lines, a logical way was required to decide whether the block should be included. Since the population data were recorded by polygon-shaped census blocks while the hazmat release boundaries were curved lines, these two different shapes inevitably caused erroneous results when estimating the affected population. Thus, in this research the centroid concept was used to decide whether the block should be counted or not. If the block centroid was inside the cutoff line, it was included for the calculation of the affected population. This method was used because selecting block groups only within the boundary lines resulted in significant underestimation of the affected population. In other words, block groups whose areas were mostly included in the hazmat release boundaries would have been excluded if the centroid method had not been used. Even though this method overestimated the affected population, it was not as significant as the problem of underestimation when only considering blocks that were totally included. Table 11 presents the affected populations in different chlorine concentration levels. Since patterns of hazmat release accidents were fan-shaped, the affected populations increased as the distance from the source increased.

Table 11 Affected Populations in Different Chlorine Concentration Levels

Affected populations	Emergency Response Planning Guidelines (ERPG) for Chlorine Concentration		
	ERPG-3: 20 ppm	ERPG-2: 3 ppm	ERPG-1: 1 ppm
Number of People	1,355 (4,267)	3,181 (15,015)	4,475 (24,509)
Housing Units	659 (1,934)	1,525 (6,281)	1,998 (8,569)

Note: The numbers in parenthesis represent total possible affected population at a 95% confidence level about wind variability.

5 DISCUSSION

Through the research work, the proposed methods found solutions about problems of the previous research work. Many researchers have tried to conduct operation research for hazmat transportation problems to provide optimized routes. However, most of them gave much attention to local routing problems in the given network. Even, the operation research did only consider limited factors such as travel time or cost in multi-criteria analysis. The raster analysis technique proposed in this thesis allows considering numerous factors together in cell-based raster formats. This area-based identification tool can also be applicable to broad areas.

In the previous research, hazmat transport prediction models were mostly applied for a single mode of transportation. Even though some researches had investigated hazmat routing methods to apply for all transportation modes, the procedures became complex and included intricate equations. In this proposed GIS-based hazmat transportation risk identification method, different modes of transportation such as rail, pipeline or even water transportation could be easily integrated and analyzed together within a specified study area due to the map-based GIS integration techniques.

The proposed methods developed an effective tool to deal with hazmat transportation route risk assessment. However, the analysis process also leaves some possible limitations behind to be dealt. When weighting and combining different raster layers in the multi-criteria analysis process, some factors may not change the results while others may change the result significantly due to their different sensitivity to the result. For instance, it is probable that the locations of fire stations or schools may not be significantly influential to the result because they are evenly spaced across the study area. On the other hand, locations of hazmat facilities would affect the result more since they are likely to be located in a certain area for safety purposes. Thus, establishing a sophisticated weighting scheme is required to produce a more accurate result.

In addition, input layers identified for inclusion in the analysis could be based on some objective indices such as Federal Emergency Management Agency (FEMA) requirements. In this research, eight possible different datasets were considered, but there may be some other variables which can also be included. A list of critical facilities provided by U.S. Department of Health Human Services (DHHS) could be used to find all possible variables being included for the analysis.

Finally, in the hot spot analysis, the straight lines among accident points were used to calculate the spatial relationship. However, it is more accurate to use network-based lines since the accident points are inter-related along the roadway network. In addition, these straight lines do not consider the 3-Dimenssional features such as interchanges, bridges, or tunnels. Since the accident points were geocoded with only x and y coordinates, the third factor, or height could be used to identify the spatial relationship among accidents more accurately.

6 CONCLUSIONS

Modern industrial processes require hazardous materials and their transportation across highways carries a certain amount of risk to those living in relative proximity of those highways. Assessment of routes that pose the highest risk from transportation of hazardous materials is needed for more informed planning and response. There have been studies dealing with identifying optimized hazmat routes and estimation of affected areas using diverse models. However, the direct identification of vulnerable areas with respect to hazmat releases from truck accidents has not been fully researched. In addition, a simplified combination of quantitative risk analysis using historical accident data and the multi-criteria analysis has not been fully exploited.

In this research three main analyses were conducted. First, historical truck accident data were analyzed with spatial statistical concepts. Instead of creating accident density maps directly, a spatial data analytical technique called hot spot analysis using the Getis-Ord Gi* statistic was used to determine where the high or low severity accidents were clustered. The accident density map reflected the accident severity levels. That is, high severity accidents were weighted more based on density. The density map provided not only where the accidents were clustered but also where the high or low severity accidents were clustered. The locations of the clusters were considered to be more vulnerable areas in terms of hazmat transportation. This density map then became one of the inputs for multi-criteria analysis where diverse criteria were transformed into raster layers. Through the analysis, it was found that the high severity accidents were more clustered near the intersections and interchanges on major highways while low severity accidents were clustered in downtown area where the roadway network is complex with low speed limits.

Second, all the inputs to identify vulnerable areas were analyzed in GIS through multi-criteria analysis. The raster analysis technique using small cells was used to discern cell-based vulnerable areas in terms of hazmat transportation release accidents. By all the cell values in the input raster datasets, the integrated result raster provided vulnerable areas in Lancaster County. These areas were then used to select the potential risky routes for the potential hazmat truck accidents. That is the routes that were overlapped with the identified vulnerable areas were found and designated to be potential risky routes in terms of hazmat truck accidents. This area-based identification tool for potential risk-prone routes for hazmat release accidents also allows analysts to consider multimodal hazmat transportation.

Finally, impact analysis identified hazmat release patterns and their consequences by calculating the affected areas and population. In this analysis chlorine was used for the calculation of the release pattern in a theoretical accident. ALOHA modeling software for hazmat was used to produce the hazmat footprint via a virtual scenario. When compared to the previous methodology using a simple circle to estimate the affected area and population, the proposed method using ALOHA effectively quantified the more reasonable affected areas and vulnerable population by considering wind, terrain and chemical source information. The result created three different hazmat concentration zones according to Emergency Response Planning Guidelines (ERPG). Also, possible variation zones with statistical uncertainty for wind direction at a 95% confidence level were also estimated. The created different distances can be used for the hazmat evacuation distance planning by quantifying the affected population and areas.

Even though the presented procedure in this research provides an effective tool to identify the potential risky roadway segments and the affected areas and population for hazmat evacuation plans, there are future research topics to be explored. The applied weights for each criterion layer in the multi-criteria analysis may be modified for different regions where the analysis is conducted. Thus, a universal application process to apply the concept to other areas could be researched henceforward. That is, the weight for each input datum could be area-based to accurately mirror reality by creating local factors. Also, the input system for real-time data should be deployed to establish an immediate evacuation planning tool. In particular, integration of the input system for varying traffic and weather conditions would provide real-time evacuation planning process to local governments when hazmat truck incident occur in the area.

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APPENDICES

Appendix A: Toxics Release Inventory (TRI) in Lancaster County

Facility Name	Address	Zip	Latitude	Longitude
LINCOLN ELECTRIC SYSTEM TERRY BUNDY GENERATING STATION	7707 BLUFF RD	68517	40.9097	-96.6128
PARKER HANNIFIN CORP	252 N 134TH ST	68520	40.814167	-96.538333
KAWASAKI MOTORS MANUFACTURING CORP USA	6600 NW 27TH ST	68524	40.877992	-96.758428
NEBRASKA PUBLIC POWER DISTRICT SHELDON STATION	4500 W PELLA RD	68368	40.55202	-96.7829
LAND O'LAKES PURINA FEED LLC - LINCOLN	5500 N COTNER BLVD	68507	40.868222	-96.618468
TELEDYNE ISCO A BUSINESS UNIT OF TELEDYNE INSTRUMENTS INC	4700 SUPERIOR ST	68504	40.857354	-96.655028
VEYANCE TECHNOLOGIES INC	4021 N 56TH ST	68504	40.853264	-96.644184
MOLEX INC	700 KINGBIRD RD	68521	40.852101	-96.738394
LESTER ELECTRICAL	625 W A ST	68522	40.799069	-96.728859
LINCOLN INDUSTRIES INC	600 W E ST	68522	40.803125	-96.728391
ADM	7800 THAYER ST	68507	40.866447	-96.620111

PFIZER INC	601 W CORNHUSKER HWY	68521	40.835588	-96.728228
SCHNEIDER ELECTRIC USA	1717 CENTERPARK RD	68512	40.765942	-96.697879
TRI-CON INDUSTRIES LTD	4000 NW 44TH ST	68524	40.854167	-96.781111
ADM MILLING	540 S ST	68502	40.791582	-96.714309
CLEAVER-BROOKS INC	6940 CORNHUSKER HWY	68507	40.869427	-96.626847
YANKEE HILL BRICK MANUFACTURING CO	3705 S CODDINGTON AVE	68522	40.777	-96.7495
BEDIENT PIPE ORGAN CO	1060 SALTILLIO RD	68430	40.697222	-96.705278
MOLEX INC	1400 W BOND CIR	68521	40.844323	-96.740403
STANLEY SENIOR TECHNOLOGIES	1620 N 20TH CIR	68503	40.829167	-96.691944
FARMLAND FOODS INC (COOK'S HAM)	200 S 2ND ST	68508	40.8125	-96.7169

Appendix B Result of Incremental Spatial Autocorrelation in 30 different distance bands

OBJECTID	Distance(m)	Distance(feet)	MoransI	ExpectedI	Variance	z_score	p_value
1	100	328.084	0.011177	-0.002061856	0.000739	0.487011	0.62625
2	150	492.126	0.01562	-0.001733102	0.000778	0.622033	0.53392
3	200	656.168	0.02531	-0.001618123	0.000741	0.989382	0.322476
4	250	820.21	0.033482	-0.001485884	0.000745	1.281044	0.200178
5	300	984.252	0.018936	-0.00140056	0.000705	0.765929	0.443719
6	350	1148.294	0.053556	-0.001328021	0.000702	2.071437	0.038318
7	400	1312.336	0.057057	-0.001270648	0.000668	2.257363	0.023985
8	450	1476.378	0.063886	-0.001240695	0.000618	2.618806	0.008824
9	500	1640.42	0.060688	-0.001216545	0.000567	2.599235	0.009343
10	550	1804.462	0.062848	-0.001201923	0.000522	2.804334	0.005042
11	600	1968.504	0.056293	-0.001180638	0.000496	2.579562	0.009893
12	650	2132.546	0.051912	-0.001173709	0.000449	2.506454	0.012195
13	700	2296.588	0.052179	-0.00116144	0.000411	2.632039	0.008487
14	750	2460.63	0.045733	-0.001152074	0.000382	2.399401	0.016422
15	800	2624.672	0.042579	-0.001146789	0.000349	2.340353	0.019266
16	850	2788.714	0.035722	-0.001142857	0.000317	2.071476	0.038314
17	900	2952.756	0.029185	-0.001141553	0.000287	1.789503	0.073534
18	950	3116.798	0.024577	-0.001140251	0.000266	1.576795	0.114843
19	1000	3280.84	0.019808	-0.001136364	0.000254	1.313059	0.189163
20	1050	3444.882	0.020209	-0.001135074	0.00023	1.406692	0.159519
21	1100	3608.924	0.016898	-0.001135074	0.000216	1.225808	0.220271
22	1150	3772.966	0.016212	-0.001133787	0.000205	1.210382	0.226133
23	1200	3937.008	0.012177	-0.001132503	0.000196	0.951204	0.341501
24	1250	4101.05	0.016614	-0.001128668	0.00019	1.285979	0.19845
25	1300	4265.092	0.014729	-0.001128668	0.000182	1.175892	0.239638
26	1350	4429.134	0.016648	-0.001127396	0.000173	1.351216	0.176626
27	1400	4593.176	0.014115	-0.001126126	0.000165	1.185792	0.235705
28	1450	4757.218	0.016186	-0.001126126	0.000155	1.389855	0.164573
29	1500	4921.26	0.01774	-0.001124859	0.000149	1.543679	0.122666
30	1550	5085.302	0.018386	-0.001124859	0.000142	1.636035	0.101832

Appendix C ALOHA Text Summary

SITE DATA:
Location: LINCOLN, NEBRASKA
Building Air Exchanges Per Hour: 0.47 (user specified)
Time: July 19, 2014 1003 hours CDT (user specified)

CHEMICAL DATA:
Chemical Name: CHLORINE Molecular Weight: 70.91 g/mol
AEGL-1 (60 min): 0.5 ppm AEGL-2 (60 min): 2 ppm AEGL-3 (60 min): 20 ppm
IDLH: 10 ppm
Ambient Boiling Point: -30.9?F
Vapor Pressure at Ambient Temperature: greater than 1 atm
Ambient Saturation Concentration: 1,000,000 ppm or 100.0%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
Wind: 6.15 miles/hour from NW at 164.04 feet
Ground Roughness: open country Cloud Cover: 5 tenths
Air Temperature: 75?F Stability Class: B
No Inversion Height Relative Humidity: 75%

SOURCE STRENGTH:
Leak from hole in horizontal cylindrical tank
Non-flammable chemical is escaping from tank
Tank Diameter: 4 feet Tank Length: 36 feet
Tank Volume: 3,384 gallons
Tank contains liquid Internal Temperature: -30?F
Chemical Mass in Tank: 39,642 pounds
Tank is 90% full
Circular Opening Diameter: 2 inches
Opening is 40 inches from tank bottom
Release Duration: 16 minutes
Max Average Sustained Release Rate: 569 pounds/min
(Averaged over a minute or more)
Total Amount Released: 1,321 pounds
Note: The chemical escaped as a mixture of gas and aerosol (two phase flow).

THREAT ZONE:
Model Run: Heavy Gas
Red : 1599 yards --- (20 ppm = ERPG-3)
Orange: 1.9 miles --- (3 ppm = ERPG-2)
Yellow: 2.8 miles --- (1 ppm = ERPG-1)