Demonstration of a Geographic Information System Methodology to Quantify Risk Factors for the Transportation of Nuclear Materials

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ABSTRACT

The risk associated with the transportation of nuclear materials can be impacted by many factors of the transportation system, as well as by the area through which the materials may travel. Informed decision-making, with regard to the safety of a given route, requires a quantitative evaluation of pertinent information, or conditions. Geographic information systems (GIS) are often used to display spatial information. The utility of a GIS can be enhanced by the ability to combine and quantify the various data layers of the GIS. The authors have previously developed a methodology that can be used to quantify the conditions that impact risk over a segment of a transportation route. The methodology aggregates the impact of a condition based on the magnitude of the impacting condition and its location with respect to the transportation corridor. This paper is a proof-of-concept demonstration for the methodology for the factors of the amount of traffic on the roadway segment, the curves and elevation changes of the roadway, and the population in the vicinity of the roadway. The methodology is particularly suited to a comparison of alternative routes for decision making.

INTRODUCTION

This paper represents a demonstration of the methodology previously developed and presented by the authors [1] as a process for evaluating alternate transportation routes for nuclear materials. There are many factors that impact the risk associated with different transportation routes. Some of the factors are associated with the infrastructure itself, and some are associated with where the infrastructure is located. Both of these types of factors can be evaluated via a geographic information system (GIS) [2] that allows for the spatial analysis of the infrastructure itself and where the infrastructure is located.

Specifically, the authors present the results of quantifying two separate parameters associated with risk and of aggregating the information for decision making.

METHODOLOGY

Route comparison and decision-making for the transportation of nuclear materials may involve many parameters [3]. Any given route may be associated with parameters that contribute more or less to the overall risk, and tradeoffs must be made in the overall decision making [4]. As previously reported by the authors [1], the goal of the route comparison discussed here is not to calculate a specific risk but to compare the contributing factors of various routes if one needs to move materials from one point to another. For example, one might consider rural highways because of the lesser population along the route but the potential risk along that route might increase due to an absence of medians and/or access controls.

Process Steps

The existing methodology includes the following steps: (1) identification of potential parameters for analysis, (2) collection and analysis of spatial information, (3) assessment of the utility of the spatial information for decision making, (4) assessment of the completeness of the set of parameters (and the subsequent identification, collection, and analysis of additional data, as appropriate), (5) data standardization, (6) weighting of parameters, and (7) aggregation of parameters [1]. The demonstration discussed here provides examples of developing information for use in route selection (analysis of the spatial information), its standardization, and the application along a linear transportation route. The data standardization permits multiple parameters to be made dimensionless and represented within a scale from 0 to 1 for aggregation of risk factors from multiple parameters.

Parameters Quantified

Two parameters were characterized in this demonstration for the analysis of two arbitrarily selected alternate roadway routes from Cincinnati, OH to Paducah, KY [5]. These two routes (Route 1 and Route 2) are shown in Figure 1.

The first parameter demonstrated is the number of individuals potentially affected by a transportation incident. This parameter has components of both the population in an entire Census block group and a fraction of the population in the Census block group that is located close to the roadway and most likely be affected by the incident [6]. Roadway segments in both rural and urban locations were evaluated. The block groups (physical areas with populations of between 600 and 3000) in urban areas are usually smaller than in rural areas, indicating greater density of population (Figure 2). A route that potentially exposes more individuals to the impacts of a transportation incident may contribute more to overall risk than a route with a lower impact factor.

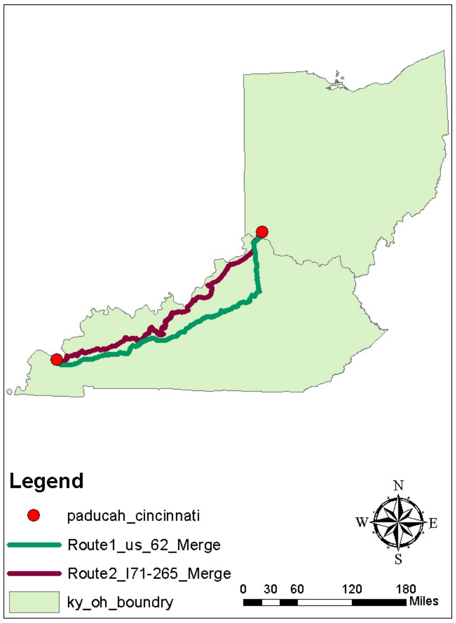
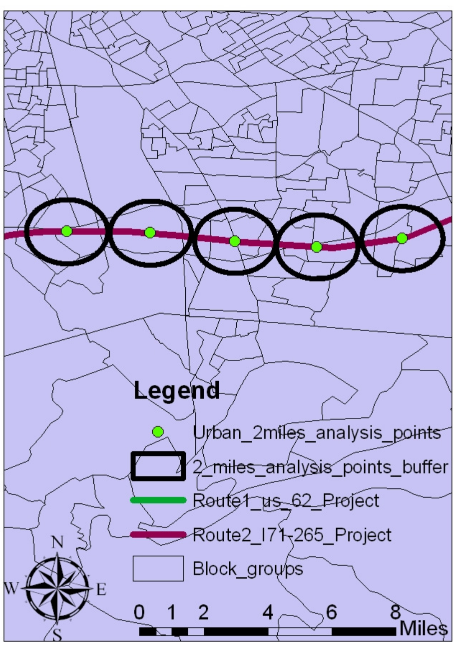


Figure 1. Study area.



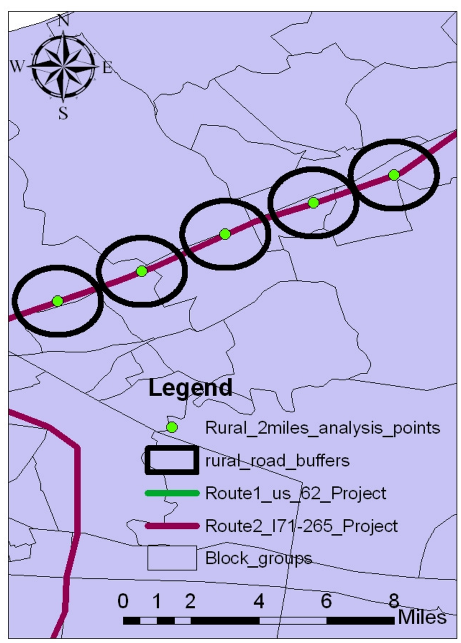


Figure 2. Quantification of person/mile parameter in urban and rural areas.

The second parameter addressed is the impact of the types of roadway over which materials are transported on the likelihood of a transportation incident. The demonstration focuses on the two physical characteristics of whether or not the highway has limited access (i.e., contains ramps for the controlled entrance or exit of vehicles) and whether or not lanes for travel in different directions are separated (i.e., is there the potential for head-on collisions during vehicle passing). Limited portions of Routes 1 and 2 that are used for the type of highway comparison are shown in Figure 3. Some highway incidents may result from individual driver errors when entrance or exits ramps are not provided or when vehicles must move into an oncoming traffic lane in order to pass another vehicle. Both of these structural conditions may then be seen as potentially contributing to the risk associated with a particular transportation route. A route segment with both limited access and with a median would be considered to represent less risk than a segment that had limited access or a median, and a segment with limited access or a median would represent less risk than a segment that had neither limited access nor a median.

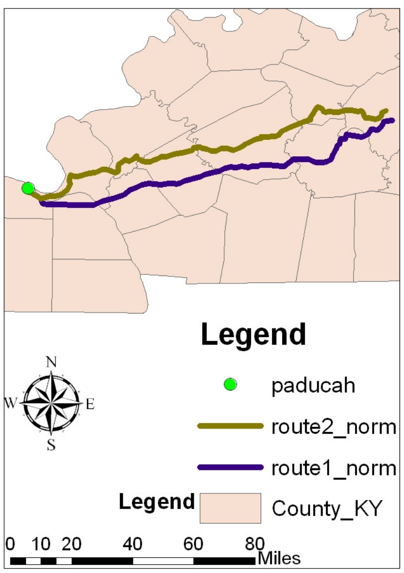


Figure 3. Limited portions of Route 1 and Route 2 used for type of highway comparison.

Data Standardization

An issue that arises is how to standardize various types of data in order to produce a set of dimensionless parameters that can be aggregated to represent the overall risk of a transportation route. Data standardization is a means by which to represent values on a scale of from 0.0 to 1.0:

$$S_i = (X_i - X_{min})/(X_{max} - X_{min})$$

where Si is the standardized value for the original value X_i, X_{min} is the lowest value, and X_{max} is the highest original value. Standardization requires the comparison of an individual parameter value against the minimum and maximum values that occur for that value. One option for data standardization is to compare a value against a theoretical minimum and maximum in order to establish where that value is located in the overall universe of that attribute. This procedure could be used in the route selection process to guide the identification of alternate routes that reduce risk factors.

RESULTS

Population and Distance

A GIS buffer analysis [7] is used to quantify the population potentially affected by a nuclear transportation incident. The five circles created by buffer analysis indicated in both parts a (urban) and b (rural) of Figure 2 are the locations where the population and distance parameter were evaluated. Adjacent two-mile diameter circles can be considered to represent a continuous evaluation of the parameter. The parameter itself is in units of persons/mile so that areas with larger numbers of individuals located at shorter distances from the specific analysis point in the center of the circle produce a larger number, and thus indicate greater risk. The parameter was calculated by overlaying the analysis circles on the block group data layer in a GIS. Only a portion of a block group may lie within the analysis circle, and so that population must be assigned to the circle. The centroid of the portion of a block group that exists within a circle is identified and its area is determined [8]. The ratio of the block group area within the circle to the area of the entire block group is the faction of the block group population that is assigned to that particular circle. The distance of the centroid from the analysis point is a measure of how close that population is to a potential incident location. Centroids for both the urban and rural locations are shown in Figure 4, while a portion of the table used to calculate the persons/mile parameter is shown in Table 1. Table 2 lists the persons/mile parameter value for each of the 10 analysis points (5 urban and 5 rural).

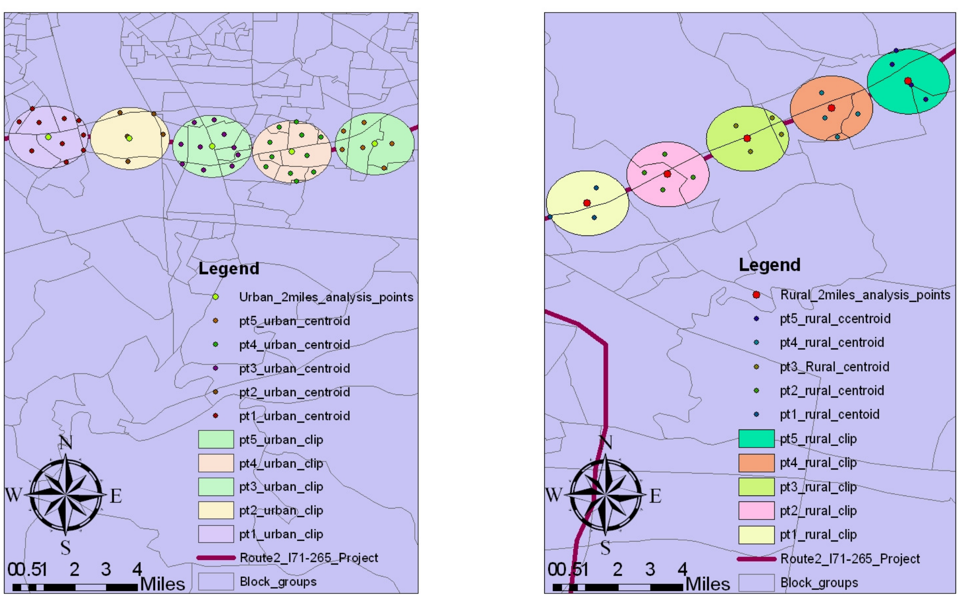


Figure 4. Centroids of urban and rural locations.

Table 1. Calculation of persons/mile parameter for urban area point 2.

Census Tract	Block Group	Total Population	Total Area (sq. meters)	Intersected Area (sq. meters)	Intersected Population	Distance From Centroid (mi)	Persons/ Mile	Standardized Value
11901	4	3,163	6516190.896	5865894.52	2847.342	0.08	35591.77	
12001	2	1,810	15289723.49	1203245.98	142.4404	0.76	187.4216	
11905	2	2,378	2186674.994	538472.021	585.5860	0.86	680.9140	
11905	1	2,051	1284230.604	2214.53034	3.536749	1	3.536749	
11901	3	5	17009123.67	526216.461	0.154686	0.86	0.179868	
						Total Persons/ mile	**36463.82**	**1**

Table 2. Persons/mile parameter and standardization values.

Urban Area Analysis Points	**Persons/Mile**	**Standardized Value**
1	12916.69254	0.321367
2	36463.82801	1.0
3	19674.17123	0.516119
4	10373.0539	0.248058
5	6104.993627	0.125052
Rural Area Analysis Points	**Persons/Mile**	**Standardized Value**
1	2201.92907	0.012565
2	1765.956943	0.0
3	2062.640199	0.00855
4	4257.00425	0.071793
5	6681.461294	0.141666

Data standardization can be performed based on the individual parameter values in Table 2, where one of the 10 values will be the minimum (standardized value of 0.0) and one will be the maximum (standardized value of 1.0). The entire 10-mile urban stretch is characterized with an average standardized value of 0.442, while the 10-mile rural stretch is characterized as 0.047. The calculations based on the actual minimum and maximum results in the two anomalous values of 0.0 and 1.0. The anomalies make it difficult to characterize an entire route by averaging the standardized values. An alternative strategy might be to evaluate each parameter value based on theoretical minimum and maximum values and/or to apply the process over the entire route in order to limit the impact of a few outlying values.

The similarity of the standardized values in the areas when the population block groups are uniformly small (urban areas) or uniformly large (rural areas) suggests that fewer analysis points could be required than in locations where there is a mix of small and large Census block groups.

Road Characteristics

Table 3 shows that any selected route may be a combination of interstate highways, U.S. highways, and state highways. Because of the different risk associated with highway design characteristics, each type of highway has been assigned a rating value to indicate a certain type of road condition and its corresponding risk. In the demonstration here, "1" indicates limited access *and* a separation between traffic moving in opposite directions, "2" indicates that a segment has either limited access *or* a separation, and "3" indicates that a segment has neither limited access *nor* traffic separation. The last column of Table 3 shows the rating that has been applied to each segment of a transportation route. The rating for a segment is the product of the travel distance and the highway characteristic rating, where a larger number indicates a greater risk.

Table 3. Calculation of roadway segment rating factors.

Feature	Name	ST	Length (miles)	Characteristic Rating	Segment Rating
Limited access Highway	Interstate Route 265	KY	6.05083028033	1	6.05083028033
Limited access Highway	Interstate Route 265	KY	5.45603205515	1	5.45603205515
Limited access Highway	Interstate Route 265	KY	1.54544975544	1	1.54544975544
Limited access Highway	State Route 841	KY	11.84269805680	1	11.84269805680
Principal Highway	US Route 31, US Route 60W	KY	4.47246846427	2	8.94493692854
Principal Highway	US Route 31, US Route 60W	KY	9.28255864608	2	18.56511729216
Other Through Highway	State Route 79	KY	9.90598290493	3	29.71794871479
Other Through Highway	State Route 85	KY	0.57059723551	3	1.71179170653
Other Highway	State Route 69	KY	5.93674955900	3	17.810248677

Data standardization of road characteristics is based on the theoretical minimum and maximum values. The theoretical minimum value is the product of the shortest travel distance of the routes being considered and the best rating (i.e., 1, for an interstate highway). The theoretical maximum value is the product of the longest route under consideration multiplied by the worst rating (i.e., 3, for a state highway). Using this standardization method, the western-most portion of Route 1, with a distance of 110 miles and no interstate highways, but with a plurality of U.S. highways receives a lower (i.e., less risky) rating of 0.463. The corresponding western-most portion of Route 2, with a similar distance of 116 miles, no interstate highways, and a greater number of state highways, receives a standardized rating of 0.917. The ratings indicate a comparison of the two routes, but also that there may be considerable risk in this portion of the trip based on highway characteristics. While one could look for a less risky route (i.e., shorter and/or with a lower highway characteristic rating), it may not always be possible as interstate highways exist in limited locations.

Standardized values must be examined over all of the evaluation parameters. An interstate highway route intersecting an urban area may be associated with greater population risk because of the individuals potentially impacted by a transportation incident. Conversely, this route may contribute less to overall risk because of the superior highway design characteristics that serve to reduce the likelihood of certain types of crashes.

CONCLUSIONS

In this paper, the authors have demonstrated the use of a methodology to quantify and aggregate risk factors associated with the transportation of nuclear materials. This demonstration utilizes the capabilities of a GIS to capture spatial relationships. Risk factors studied here include the characteristics of the transportation system (i.e., the type of highway over which the materials are transported), as well as the spatial context of the transportation (i.e., the number of persons living along a transportation route who might be impacted by an incident). Through the power of a GIS, the methodology has been used to quantify area and length information as a point characteristic and to aggregate point characteristics over a length of a roadway. The roadway linear characteristics over a particular segment were standardized to single point for easy comparison.

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