A PROOF OF CONCEPT STUDY FOR ANALYZING HAZMAT TRANSPORTATION RISKS IN AN ALL HAZARDS ENVIRONMENT

Samrat Chatterjee*
Department of Civil and Environmental Engineering
Vanderbilt University, Room 268 Jacobs Hall, VU Station B-35 1831
Nashville, TN 37235
Phone: 615-343-6001; E-mail: samrat.chatterjee@vanderbilt.edu

Mark D. Abkowitz
Department of Civil and Environmental Engineering
Vanderbilt University, Room 292 Jacobs Hall, VU Station B-35 1831
Nashville, TN 37235
Phone: 615-343-3436; E-mail: mark.abkowitz@vanderbilt.edu

ABSTRACT

Events such as the World Trade Center attacks, Hurricane Katrina, and the Minneapolis bridge collapse have amplified society’s perception of the risks affecting our lives. It has also led to the realization that a more systematic and holistic approach to risk management is needed, one that takes into consideration natural hazards, man-made accidents, and intentional acts in a single context. This paper discusses the early stage development of an all hazards risk management (AHRM) approach designed to achieve this objective, taking hazardous materials transportation risk into consideration. Utilizing established assessment methods and data sources, relevant risks are expressed in monetary terms, creating a consistent basis from which one can identify those risks that warrant priority attention. An early stage application is presented, one involving an assessment of truck transportation of hazardous materials and earthquakes as two risks threatening several areas within the State of Tennessee, to illustrate the viability of implementing an AHRM approach.

Keywords: Risk assessment, risk management, hazardous materials transportation, hazard analysis

* Corresponding author
INTRODUCTION

Over the past decade, there have been dramatic shifts in society’s view of the risks that affect our everyday lives. The attacks on the World Trade Center led to increased focus on managing security risk. Later, Hurricane Katrina struck and exposed our vulnerability to natural hazards. More recently, the Minneapolis bridge collapse has reminded us of the perils of man-made accidents.

These adverse events have demonstrated that a more traditional approach where the attention constantly shifts towards the risk-at-hand is narrow and shortsighted. As the global interactions of people, goods, and services increase (Cova and Conger, 2004), and with climate change upon us, an organized study of these events is important. To be successful, this will require breaking down the “stovepipe” mentality of managing various safety and security risks, to be replaced by adopting an all hazards approach.

The guiding principle for an all hazards risk management (AHRM) approach is that all safety and security concerns share a common objective, which is to reduce the likelihood and consequences of undesirable events so as to protect human health, quality of life and the environment. A holistic view of the problem of risk management argues that in order to develop an efficient risk management strategy, the risks posed by natural hazards, man-made accidents, and intentional acts need to be evaluated in a single, integrated framework. This enables the risk manager to make more informed and intelligent decisions about the most important risks to address and what mitigation strategies offer the greatest overall benefit-cost, while feeling confident that the decision-making process is being driven by a complete and systematic approach.

The immediate challenge in formulating an AHRM approach lies in establishing a common protocol and performance metric to quantify risks posed by various hazards. Preliminary design and testing of a methodology to accomplish this task was the primary objective of this research.
AHRM APPROACH

The implementation of an AHRM approach as described herein involves the evaluation of each relevant risk in monetary terms for the area of concern, hereafter referred to as the “risk-cost”. Note that the area of concern could be a political jurisdiction, such as a city, county or state. It could also represent a specific facility or a collection of facilities, possibly situated in diverse locations.

The all hazards risk-cost is computed by aggregating the risk-costs due to different hazard types that threaten the area of concern:

\[
Risk_{ah} = Risk_n + Risk_m + Risk_i
\]  

where:

\(Risk_{ah}\) = All hazards risk-cost

\(Risk_n\) = Natural hazards risk-cost

\(Risk_m\) = Man-made accidents risk-cost

\(Risk_i\) = Intentional acts risk-cost

Figure 1 shows a hypothetical all hazard risk-cost for an area of concern, expressed in terms of the percentage attributed to natural hazard, man-made accident and intentional act hazard types, respectively. Note that in this instance, natural hazard is not only the largest contributor to the all hazard risk-cost, but also presents the majority of the risk-cost. It would therefore be reasonable for these concerns to dominate the risk manager’s attention and resources.
Each of the three hazard types can be further divided into specific hazards. For example, natural hazards threatening the area of concern might include: (1) volcanoes, (2) hurricanes, (3) floods, and (4) earthquakes. The risk-cost of each specific hazard is added to generate the risk-cost for a particular hazard type:

\[
Risk_n^c = \sum_{k=1}^{N} Risk_{n_k}^c
\]  

where:

\( n_k \) = specific natural hazard k

\[
Risk_m^c = \sum_{k=1}^{M} Risk_{m_k}^c
\]  

where:

\( m_k \) = specific man-made accident k
\[ Risk_i^c = \sum_{k=1}^{l} Risk_{i_k}^c \]  

where:

\( i_k \) = specific intentional act \( k \)

Figure 2 shows a hypothetical natural hazard risk-cost, expressed in terms of the percentage attributed to volcanoes, hurricanes, floods and earthquakes. Based on this information, it is apparent that flood and volcano risk stand out as the major contributors to natural hazard risk-cost, and are justifiably the focal point of risk management attention.

While relatively simple in concept, the implementation of an all hazards risk assessment methodology is a formidable task. The number of specific hazards to be considered, the development of
an accepted risk assessment technique for each specific hazard, and the availability of the necessary data to implement each technique all contribute to this challenge.

As a starting point, this research focused on developing and applying an AHRM methodology to two hazard types (man-made accidents; natural hazards), focusing on one specific hazard within each type (truck transportation of hazardous materials; earthquakes), where the area of concern is a county. So as to examine potential differences in risk-cost within and across areas of concern, the development process considered three counties located in the State of Tennessee: (1) Hamblen, (2) Shelby, and (3) Smith (see Figure 3). The basis for selecting these counties was their varying demographics, truck transportation patterns and seismicity.

![Counties in TN](Figure 3. Counties in Tennessee selected for methodological development)

**TRUCK TRANSPORTATION OF HAZARDOUS MATERIALS**

Two major tasks were associated with performing the risk assessment for truck transportation of hazardous materials (hazmat) in the areas of concern: (1) estimating the percentage of trucks carrying hazmat from the total truck population, and (2) using this information to calculate hazmat truck transport
risk-cost. The data sources utilized in performing the hazmat truck transportation risk assessment were (FHWA, 2006; U.S. Census Bureau, 2007; FHWA, 2008; BTS, 2008):

(1) FHWA, 2002 Highway Performance Monitoring System (HPMS) data
(2) U.S. Census Bureau, 2002 Commodity Flow Survey (CFS)
(3) Federal Highway Administration (FHWA), Freight Analysis Framework (FAF) for Tennessee
(4) Bureau of Transportation Statistics (BTS) - National Transportation Atlas Database (NTAD).

Data compatibility is essential in performing this type of analysis, especially when it encompasses different agencies. Fortunately, linear referencing systems were available to integrate spatial data from these sources at the highway segment level.

**Percentage of Trucks Carrying Hazmat**

The steps in this process involved estimating: 1) the average trip length and number of trucks carrying hazmat to derive annual hazmat truck vehicle-miles, and 2) estimating the annual truck vehicle-miles in Tennessee. By combining this information, the percentage of truck vehicle-miles carrying hazmat cargo could be determined.

Figure 4 shows a flowchart of the calculations performed to determine annual hazmat truck vehicle-miles. To derive the average hazmat truck vehicle-miles per shipment, the percentage of all freight shipments utilizing the truck mode and the average hazmat vehicle-miles per shipment to and from Tennessee were used (USDOT, FHWA - FAF for Tennessee, 2008). To derive the number of truck hazmat shipments, the percentage of all freight shipments utilizing the truck mode and the total hazmat weight (all modes) from and to Tennessee were used to calculate the weight of hazmat transported by trucks (USDOT, FHWA - FAF for Tennessee, 2008). To convert this to the number of hazmat truck shipments, a “typical” shipment was defined as a loaded gasoline truck with a maximum
weight of 40 tons (Tennessee Department of Safety, 2008). Based on the assumptions of 9,000 gallon truck capacity and 87 percent maximum carrying capacity (taking into consideration the effect of sloshing), the maximum weight of a hazmat shipment was calculated to be 26.2 tons. This compares favorably with general practice, where it has been reported that a 40 ton truck can deliver 26 tons of gasoline to a conventional gasoline filling station (Bossel et al., 2003). The number of hazmat truck shipments (from and to TN) was then calculated by dividing the weight of hazmat transported by trucks by the maximum weight of a hazmat shipment. To determine the total hazmat vehicle-miles by truck (from and to TN), the hazmat truck vehicle-miles per shipment was multiplied by the number of hazmat truck shipments.

![Flowchart for estimating hazmat truck vehicle-miles in Tennessee](image)

**Figure 4.** Flowchart for estimating hazmat truck vehicle-miles in Tennessee

Figure 5 shows a flowchart of the calculations performed to determine the total truck vehicle-miles (from and to TN). The total truck shipment weight (all shipments) was divided by the maximum weight per truck (40 tons) to determine the total number of truck shipments (from and to TN). The truck
vehicle-miles per shipment were then multiplied by the total number of truck shipments to compute a measure of total vehicle-miles by truck (from and to TN).

![Figure 5. Flowchart for determining total truck vehicle miles in Tennessee](image)

To determine the percent of truck shipments in Tennessee carrying hazardous materials, the percentage of trucks carrying hazmat from and to Tennessee was determined by using the total hazmat vehicle-miles by truck and the total vehicle-miles by truck. The two cases where Tennessee is the state of origin and the state of destination were combined to generate a weighted average (by number of shipments). This resulted in a final estimate that 8.1 percent of truck shipments in Tennessee are carrying hazardous materials.

**Hazmat Truck Transport Risk-Cost**

The risk-cost computation for hazmat truck transport in each of the selected counties was performed at the highway segment level. HPMS attributes include the segment length and the segment
average annual daily traffic (AADT). This information led to the calculation of daily segment vehicle miles traveled (VMT) and then annual segment VMT. For a sample of roughly 8 percent of the HPMS segments in Tennessee, additional information is collected from which one can derive the average percentage of AADT attributed to single unit and combination trucks by highway functional class (see Table 1). The average truck percentages in each functional class were subsequently assumed to apply to the remaining HPMS highway segments in the State of Tennessee belonging to the same functional class. This enabled computation of annual truck VMT for each highway segment in Tennessee (see Figure 6). The percent of trucks carrying hazmat in Tennessee (computed earlier as 8.1%) was then used to compute the annual hazmat truck VMT for each highway section in each of the case study counties.

**Table 1.** Highway Functional System Code (FHWA, 2006)

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RURAL</td>
<td></td>
<td>URBAN</td>
</tr>
<tr>
<td>1</td>
<td>Principal Arterial - Interstate</td>
<td>11</td>
<td>Principal Arterial - Interstate</td>
</tr>
<tr>
<td>2</td>
<td>Principal Arterial - Other</td>
<td>12</td>
<td>Principal Arterial-Other Freeways &amp; Expressways</td>
</tr>
<tr>
<td>6</td>
<td>Minor Arterial</td>
<td>14</td>
<td>Principal Arterial - Other</td>
</tr>
<tr>
<td>7</td>
<td>Major Collector</td>
<td>16</td>
<td>Minor Arterial</td>
</tr>
<tr>
<td>8</td>
<td>Minor Collector</td>
<td>17</td>
<td>Collector</td>
</tr>
<tr>
<td>9</td>
<td>Local</td>
<td>19</td>
<td>Local</td>
</tr>
</tbody>
</table>
Figure 6. Information Used to Derive Segment Level Annual Truck VMT

Transforming annual hazmat truck traffic to a risk-cost was accomplished by referring to a recent Federal Motor Carrier Safety Administration study (Battelle, 2001). In that project, the average hazmat truck accident/incident cost per mile was calculated to be $0.14 (across all hazmat categories). The data used in the aforementioned study corresponded to calendar year 1996. The Consumer Price Index (CPI) calculator was used to update hazmat truck accident/incident cost per mile into 2006 terms, the reference year for this study (Bureau of Labor Statistics, 2008). The hazmat truck accident/incident cost per mile, when multiplied by the annual hazmat truck VMT, produced the annual hazmat truck transport risk-cost by highway segment. The annual hazmat truck transport risk-cost was calculated for the counties of Hamblen, Shelby, and Smith by aggregating the segment level data for highways located in each respective jurisdiction. Table 2 shows the results of this effort.

<table>
<thead>
<tr>
<th>County</th>
<th>Annual hazmat truck transport risk-cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hamblen</td>
<td>710,000</td>
</tr>
<tr>
<td>Shelby</td>
<td>7,404,000</td>
</tr>
</tbody>
</table>
EARTHQUAKES

The National Seismic Hazard Maps (NSHM), developed by the U.S. Geological Survey (USGS), depict the distribution of earthquake shaking levels (i.e., ground motion) with probabilities of occurrence in the United States (USGS, 2008). The bases for generating probabilistic ground motion maps are:

1. Past historical earthquakes, quaternary faults (prehistoric earthquakes), and present crustal deformation (geodetic data)
2. Tables that describe how the earthquake ground motion decreases as the distance to the earthquake increases
3. The geology of the material between the bed rock and the surface.

This leads to the calculation of a “probability of exceedance” of a given ground motion for a significant earthquake occurring at a specific location. The corresponding seismic hazard maps are contours of the ground motions plotted on a geographic grid, as shown in Figure 7. Eight levels of peak ground acceleration are represented in Figure 7, ranging from 0-1% (lowest hazard) to greater than 40% (highest hazard) of acceleration due to gravity.
The contour plot of seismic hazards affecting the State of Tennessee is presented in Figure 8. Based on this plot, each county was assigned a peak ground acceleration value. Where multiple contours intersected a county boundary, the largest of the corresponding peak ground accelerations was assigned to the county, representing a conservative measure of earthquake ground acceleration.
The USGS considers earthquakes of magnitude 5.0 or higher as the threshold of significant impact during development of the seismic hazard maps. In order to develop an association between ground acceleration and likelihood of occurrence of an earthquake of magnitude 5.0 or higher, the authors assembled a database of 5+ moment earthquakes that have occurred on the mainland U.S. from 1900 through 2007, including the geographic coordinates of the earthquake epicenter (USGS and NOAA, 2008). Using these coordinates, each earthquake was placed in its corresponding ground acceleration contour. The number of 5+ moment earthquakes was then summed and divided by the number of years in the database (i.e., 108) to arrive at an annual frequency of 5+ moment earthquakes.
per ground acceleration category. To complete the computation, the total number of square miles of the counties associated with each ground acceleration category was calculated which, when applied as a denominator, results in the annual moment 5+ earthquake frequency per square mile.

To determine the annual frequency of occurrence of a moment 5+ earthquake within a specific county, one identifies the largest ground acceleration category associated with that county, selects the appropriate annual earthquake frequency per square mile for that category, and then multiplies that number by the (total square mile) area of the county. The inverse of this annual probability becomes the corresponding earthquake return period (interval between successive earthquakes), expressed in years. Table 3 shows the annual probability of 5+ moment earthquakes and the corresponding earthquake return periods for the selected counties in Tennessee.

<table>
<thead>
<tr>
<th>County</th>
<th>Annual probability of earthquake (years⁻¹)</th>
<th>Earthquake return period (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hamblen</td>
<td>1.971E-05</td>
<td>50,725</td>
</tr>
<tr>
<td>Shelby</td>
<td>6.350E-04</td>
<td>1,575</td>
</tr>
<tr>
<td>Smith</td>
<td>1.704E-05</td>
<td>58,672</td>
</tr>
</tbody>
</table>

The consequence or loss estimation aspect of earthquake risk assessment was determined using the HAZards U.S. MultiHazard (HAZUS-MH, 2003) software, a product developed by the Federal Emergency Management Agency (FEMA). HAZUS-MH uses geographic information systems (GIS) to model the built environment against the backdrop of possible natural hazards. The HAZUS-MH methodology involves three basic components: (1) classification of different systems for inventory, (2) methods for evaluating the damage and calculating losses, and (3) databases characterizing demographics, building inventory and the regional economy (Kircher et al., 2006). The HAZUS-MH version 1.3, used in this study, contained building valuations and commercial data corresponding to
calendar year 2006. For earthquakes, based on a user-specified moment magnitude and earthquake return period, HAZUS-MH uses USGS probabilistic ground motion maps, ground motion attenuation models, building capacity curves, and fragility curves to estimate damages and losses. The HAZUS-MH methodology is outlined in Figure 9.

![HAZUS Input + Inventories = HAZUS Output](image)

**Figure 9.** Earthquake loss estimation using HAZUS-MH (Tantala et al., 2001)

HAZUS-MH separates consequential impacts into economic losses and human casualties. However, for the purposes of an AHRM approach, it is desirable to convert human casualties into monetary terms. In 1996, the National Highway Transportation Safety Administration (NHTSA) estimated that a fatality was equivalent to a loss of $2,800,000 (NHTSA, 1996). To update this estimate to 2006 terms, the CPI calculator was used by taking into consideration the impact of inflation (Bureau of Labor Statistics, 2008). This resulted in a revised 2006 estimate of $3,597,706 per fatality.

In applying HAZUS-MH for earthquake loss estimation, a moment magnitude of 6.0 was used, which represented a point at which damages level off irrespective of whether the earthquake is of higher intensity. The justification for using a moment magnitude of 6.0 was based on a sensitivity analysis
conducted for Shelby County (which has a relatively high seismic hazard), using varying moment magnitudes and return period levels. The sensitivity analysis results, displayed in Figure 10, show that irrespective of earthquake return periods (100, 250, 500, 750, 1000, 1500, 2000, and 2500 years were used), moment magnitude variations above 6.0 do not have a significant effect on consequence. On the contrary, Figure 10 shows that the return period does have a significant positive impact on the losses due to scenario earthquakes. The positive relationship between return period and losses is intuitive, since the longer the period of time between occurrences, the more undamaged infrastructure and population that is exposed.

Figure 10. Sensitivity analysis for probabilistic scenario earthquakes in Shelby County, TN

Unfortunately, earthquake loss estimation using HAZUS-MH is limited to eight discrete return period levels, ranging from 100 years to 2,500 years. Since return periods were in excess of 2,500 years in Smith and Hamblen counties and the return period for Shelby County was different from the discrete
levels, a linear regression analysis was performed with the loss values corresponding to the return period levels available in HAZUS-MH. The model of earthquake loss for Hamblen County as a response variable is:

\[ l_H = -59.609 + (0.328 \times r_H) \] (5)

where:

\( l_H \) = earthquake loss for Hamblen County in millions of dollars

\( r_H \) = earthquake return period for Hamblen County in years

The above model has an \( R^2 \) of 0.996, indicating that the model captures 99.6% of the variance in the response variable.

The model of earthquake loss for Shelby County as a response variable is:

\[ l_S = -639.194 + (14.703 \times r_S) \] (6)

where:

\( l_S \) = earthquake loss for Shelby County in millions of dollars

\( r_S \) = earthquake return period for Shelby County in years

This model has an \( R^2 \) of 0.974.

The model of earthquake loss for Smith County as a response variable is:

\[ l_{Sm} = -12.433 + (0.056 \times r_{Sm}) \] (7)

where:

\( l_{Sm} \) = earthquake loss for Smith County in millions of dollars

\( r_{Sm} \) = earthquake return period for Smith County in years

This model has an \( R^2 \) of 0.991.
The earthquake return periods calculated for the selected counties in Tennessee were substituted in the respective loss models to generate the earthquake losses. In order to generate earthquake risk-cost, the annual earthquake probability was multiplied by the estimated loss. Table 4 shows the annual earthquake risk-cost for the selected counties in Tennessee. As expected, Shelby County, which lies near a major fault and includes the City of Memphis, dwarfs the other two counties with regard to earthquake risk-cost. Note that the difference between the earthquake risk-cost for Shelby and Hamblen counties is two orders of magnitude, with the Smith County risk-cost an order of magnitude lower than that.

Table 4. Annual earthquake risk-cost

<table>
<thead>
<tr>
<th>County</th>
<th>Annual earthquake risk-cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hamblen</td>
<td>327,000</td>
</tr>
<tr>
<td>Shelby</td>
<td>14,300,000</td>
</tr>
<tr>
<td>Smith</td>
<td>56,000</td>
</tr>
</tbody>
</table>

INTERPRETATION AND DISCUSSION

The generation of risk-cost for truck hazmat transportation and earthquake hazards presents a decision-support framework where the risk manager can prioritize risks and allocate adequate resources in a systematic manner. For the proof of concept application described herein, a summary of the analysis results is shown in Table 5.

Table 5. Total annual risk-cost

<table>
<thead>
<tr>
<th>County</th>
<th>Annual hazmat truck transport risk-cost ($)</th>
<th>Annual earthquake risk-cost ($)</th>
<th>Total annual risk-cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hamblen</td>
<td>710,000</td>
<td>327,000</td>
<td>1,037,000</td>
</tr>
<tr>
<td>Shelby</td>
<td>7,404,000</td>
<td>14,300,000</td>
<td>21,704,000</td>
</tr>
<tr>
<td>Smith</td>
<td>1,286,000</td>
<td>56,000</td>
<td>1,342,000</td>
</tr>
</tbody>
</table>

From a policy perspective, these results can support two types of decisions: (1) how a state’s risk management resources should be apportioned to respective counties, and (2) how a county’s risk
management resources should be allocated towards hazard types and specific hazards. For the purposes of the following discussion, it is assumed that the State of Tennessee is comprised of only Shelby, Hamblen and Smith counties, and that the truck transportation of hazardous materials and earthquakes are the only hazards threatening the state.

Resource Allocation at the State Level

An inter-county assessment of risks can provide a basis for the state risk manager to effectively allocate risk management resources among respective counties. Figure 11 shows the overall risk management resource allocation based on total annual risk-cost. Shelby County has the highest overall risk-cost and therefore should command the largest share of the risk management resources (90%) distributed by the State of Tennessee. Similarly, Hamblen and Smith counties would receive 4% and 6% of the state allocation, respectively.

Figure 11. Risk management resource allocation among counties based on annual risk-cost
Resource Allocation at the County Level

The intra-county assessment of risks can provide the county risk manager with a means for effectively allocating risk mitigation resources due to hazards afflicting the particular county. Figure 12 shows the corresponding resource allocations at the specific hazard level, based on risk-cost, for each county. For Hamblen County, 68% of the risk management resources would be applied toward mitigation of hazmat truck transport risks, with the remainder allocated to earthquake risk management. On the contrary, the majority of risk management resources in Shelby County would be applied to earthquake risk mitigation (66%). In Smith County, nearly all (96%) of available risk management resources would be utilized on hazmat truck transport.

Figure 12. Risk management resource allocation within county based on annual risk-cost
CONCLUSION

The described AHRM methodology and its subsequent case study application represent a first step towards development of a more comprehensive and systematic approach to analyzing societal risks due to multiple hazards. The ultimate goal is to achieve an AHRM approach that can lead to successful investment in risk mitigation strategies, by focusing attention and resources on the most important hazards threatening an area of concern, whether applied by a government or industry entity. Although the application described herein was limited to evaluating the risk-cost of earthquake and truck hazmat transportation hazards in three counties within the State of Tennessee, it demonstrates the potential of implementing a holistic and systematic framework for analyzing risks due to multiple hazards, including other transportation commodities and modes. Several agencies gather data that, if utilized appropriately, can help develop this more comprehensive risk management approach and allow decision makers to make efficient and effective policy and resource allocation decisions.

ACKNOWLEDGEMENTS

This research was sponsored by The Southeastern Transportation Center (STC). The authors express our gratitude to the STC project monitoring committee for their involvement in this project. The cooperation of FEMA, FHWA and USGS staff in providing software, data and technical information used in this study is also appreciated.

REFERENCES


