Truck Shipment Risks for Assessing Hazardous Materials - A New Paradigm Incorporating Safety and Security

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Recent terrorist events, most notably September 11, 2001, have taught us that transportation risk management must be performed with a different lens to accommodate terrorism scenarios that would have previously been considered unlikely to warrant serious attention. Given these circumstances, a new paradigm is needed for managing the risks associated with highway transport of hazardous materials. In particular, this paradigm must: 1) more explicitly consider security threat and vulnerability, and 2) integrate security considerations into an overall framework for addressing natural and man-made disasters, be they accidental or planned.

This paper summarizes the results of a study sponsored by the U.S. Department of Transportation, Federal Motor Carrier Safety Administration for the purpose of exploring how a paradigm might evolve in which both safety and security risks can be evaluated as a systematic, integrated process. The work was directed at developing a methodology for assessing the impacts of hazardous materials safety and security incident consequences when transported by highway. This included consideration of the manner in which these materials could be involved in initiating events as well as potential outcomes under a variety of release conditions. The methodology is subsequently applied to various classes of hazardous materials to establish an economic profile of the impacts that might be expected if a major release were to occur. The paper concludes with a discussion of the findings and implications associated with this effort.

RISK ANALYSIS

Treating safety and security risk assessment under a single, all-hazards approach requires a system-oriented perspective. Figure 1 shows a generalized HM highway incident flow diagram that captures that perspective. This chart depicts the following logical chronology of an event: The first consideration is whether the release is unintentional (accidental) or intentional (terrorist-induced). In both instances, the type of material involved and the size of the shipment become important parameters. For an unintentional release, depending on the nature of the HM, a spill can result in one or more of the following outcomes: 1) fire, 2) explosion, 3) toxic release, 4) radioactive release, or 5) infectious release. Based on the pathway through these components and interactions, release impacts can be potentially widespread, affecting human health, ecology, economic interests and travel mobility. The process does not consider emotional, political, and social "costs" associated with such releases. The current U.S. Department of Transportation (USDOT) hazard classification scheme is structured to segregate incompatible materials (CFR, 2003) and manage these unintentional acts.

As shown in Figure 1, if the event is terrorist-driven, different conditions may apply. First is the question of whether the quantity of the material being subjected to the intentional act is large enough to cause a major consequence. Intuitively, different types of HM will have different threshold quantities. If a terrorist were to steal a shipment of hazardous material and the quantity was less than a threshold quantity, this act alone may have little or no impact; additional material would have to be obtained.

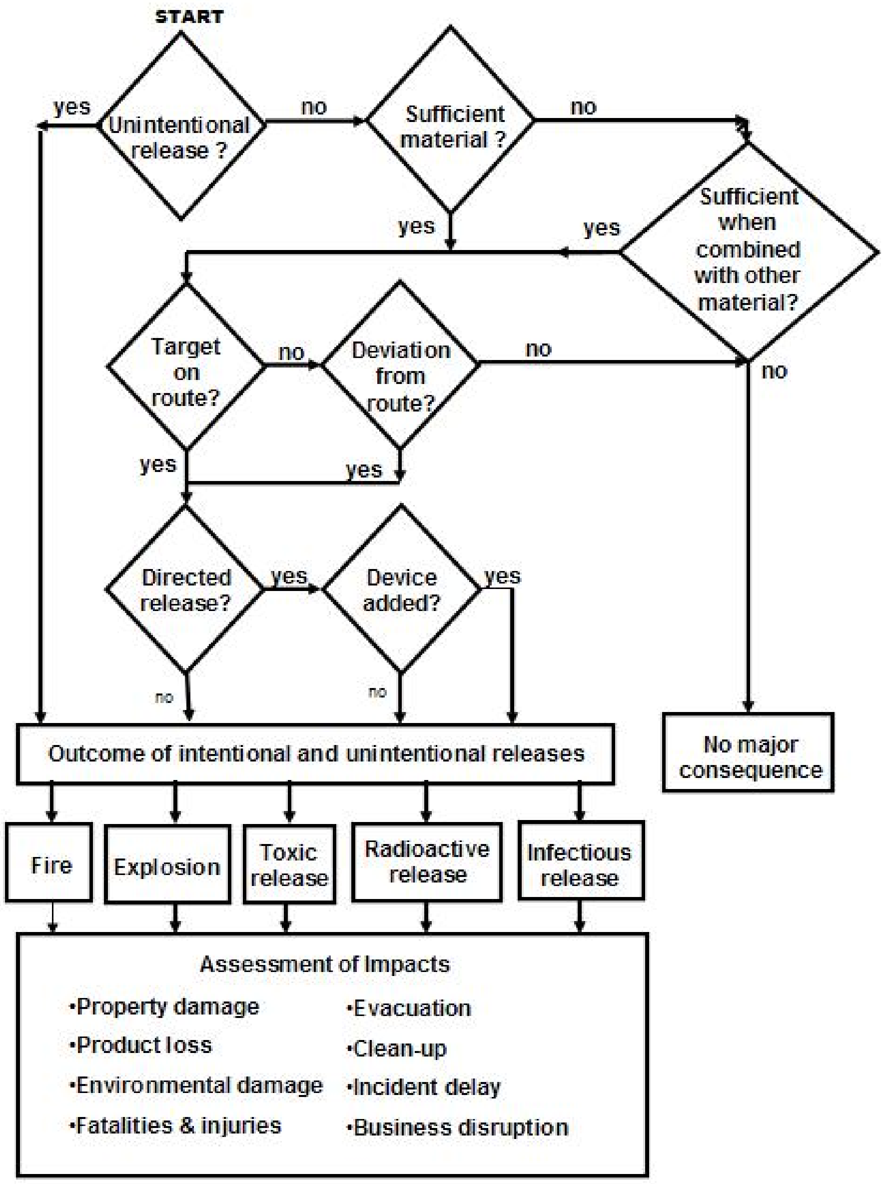

Figure 1. Hazardous Material Highway Incident Flow Diagram

The next consideration is whether the incident occurs on the shipment route or must be diverted to affect the desired target. This is followed by whether or not the intentional act is directed at a specific target. If the intentional act is undirected, the same accident could occur as an unintentional act. For example, an act would be undirected if a truckload of explosives detonated in front of a building on a route normally used for hazardous material transport. It such an incident occurred, it would be difficult to distinguish an intentional act from an unintentional one. A "directed release" is purposefully placed in close proximity to the target, distinguishing it from an undirected release. An example of a directed release would be one in which load of explosives is driven around barriers and detonated very close to the target. The final parameter shown in Figure 1 considers the case where the terrorist uses a device to detonate another hazardous material. Once these distinctions are made, the chronology progresses much like the unintentional release logic. The hazardous environments produced, although augmented, may be a fire, explosive, toxic, radioactive, or infectious; for each hazardous environment, possible impacts are assessed.

It is important to note that while the types of outcomes may be the same, i.e. fatalities, the consequences (impacts) are expected to be more severe for intentional acts because the event is more likely to be intended for a specific exposure (e.g., heavily populated area, major structure, etc.). The model considers four types of incidents, ordered by severity.

1 Reasonable unintentional releases – the result of a traffic accident.
2 Reasonable worst case unintentional releases – the result of a traffic accident in a highly populated area.
3 Reasonable worst case intentional but undirected releases – the result of a purposeful "accident" resulting in a release in a highly populated area on the route of travel.
4 Reasonable worst case intentional and directed releases – the result of a purposeful "accident" resulting in a release which is directed at a specific attractive target.

The term "reasonable" is used to bound worst case scenarios to those that are considered plausible and with a probability of occurrence that is high enough to be formally considered in the risk assessment. The following subsections address the information that would be needed to quantify these four types of incidents and whether or not a new HM classification scheme would be needed to classify the hazards associated with these four types of incidents.

SAMPLE FLOW DIAGRAM. Figure 1 is intended to be a generic figure that is applicable to all types of hazardous material. To address whether Figure 1 could be quantified, it was found advantageous to develop event trees for the various classes of hazardous material. These event trees contain the same risk components shown in Figure 1 but, as would be expected, not all the risk components are applicable for all hazardous materials. The event tree for poisonous by inhalation (PIH) materials, shown in Figure 2 contains branches asking if the event is intentional, if sufficient material is present in a typical shipment, if the target is on a shipment route, if it is a directed release and if the release point is inside or outside. The event tree does not include a branch for whether a dispersal device is included because many PIH materials are shipped under pressure. In the event tree developed for insensitive explosives, the branch for adding a detonator is included because a detonator must be added for these materials to mass detonate.

In Figure 2, at the far right of the tree is the final outcome for each unique pathway. They are numbered sequentially. For example, in the case of path 1, the final outcome is described as "outside casualties," meaning that all casualties are likely to occur "outside" any buildings or facilities and not involve any people indoors.

The event trees were developed to identify the parameters that would have to be quantified to evaluate the potential risks associated with intentional and unintentional acts involving various classes of hazardous material. Some branches are quite easy to quantify. The event tree structure also affords the opportunity to assign branch probabilities. For example, the probability that a fire or explosion will occur following an accident can be estimated in the United States by querying government maintained accident databases. Utilizing demographic data and information on common HM transport routes, reasonable estimates of the probability that an HM vehicle will pass close to an attractive target can be made. However some branches are difficult to quantify. The most difficult branch probability to estimate would be that associated with the probability of an intentional act, particularly given the lack of historical data. A possible approach to quantifying this branch is presented in the Findings and Implications section. The following subsections will address how threshold quantity levels can be specified, how to address the various types of reactions, whether new HM categories are needed, and how to assess any differences in consequence severity when considering intentional as opposed to unintentional acts.

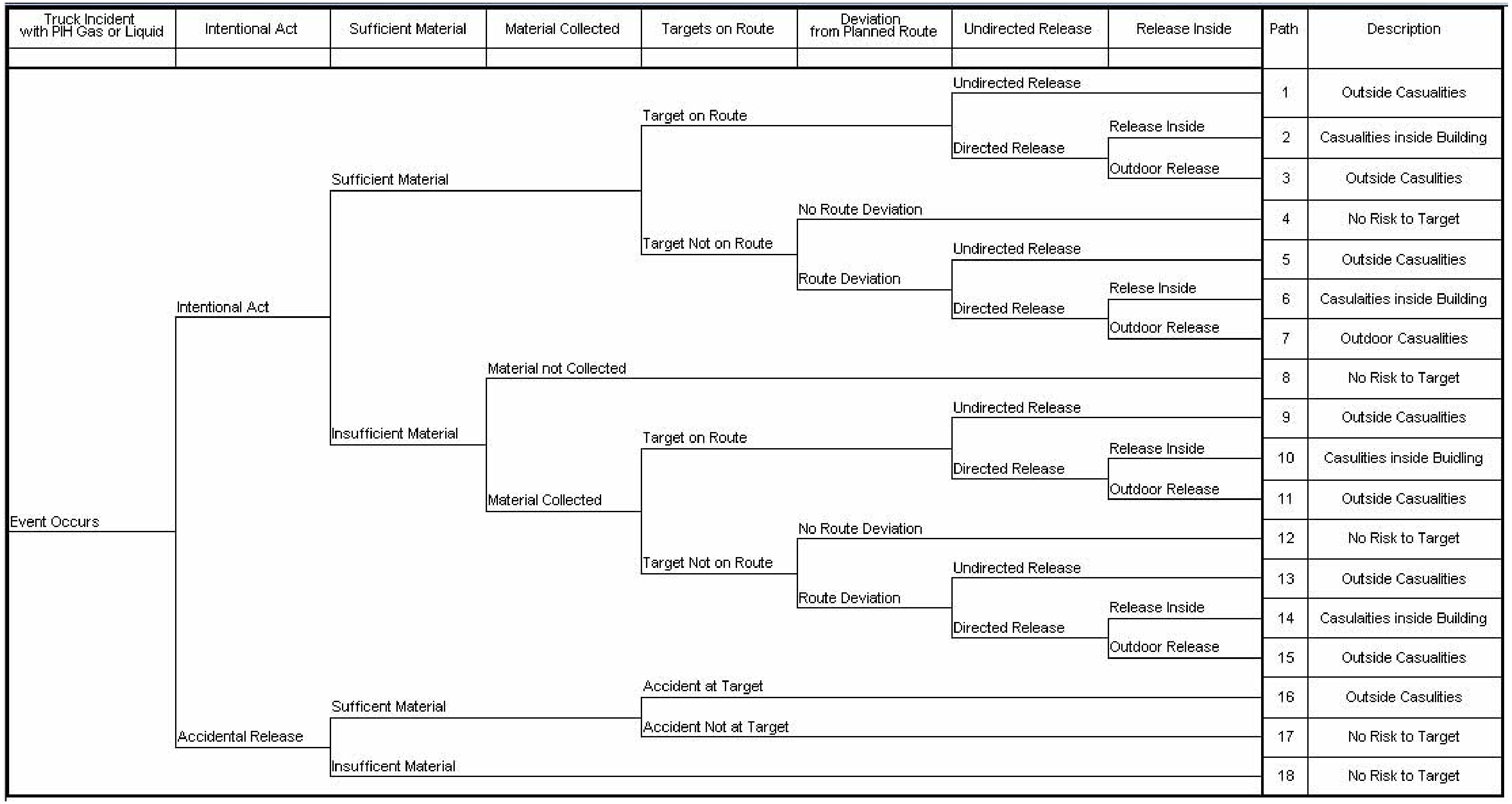

Figure 2. Event Tree for PIH Material Incident

DIRECT HAZARD. If sufficient material is present, the chemical poses a direct hazard. A report by the International Atomic Energy Commission, (IAEA,1998) is used as a basis for establishing when one material is present in sufficient quantity to present a direct hazard. The report termed that amount a "threshold quantity". Using the criteria developed in this report, a truck containing 10,000 kgs. of aniline has sufficient material to produce a major consequence for either an unintentional release or an intentional act. Conversely, a shipment of 100 kgs. of sodium cyanide, unless combined with other shipments, would not be considered a direct hazard.

REACTIONS. The question of consequence enhancement from the mixing of incompatible chemicals was systematically addressed in a report prepared to assess the need to segregate various hazardous materials in a train consist, (Battelle, 1992). This report considered the potential consequences if the accident resulted in mixing any two of the top 125 hazardous materials commonly shipped by rail in the United States. This assessment also considered possible precursor reactions. Overall, adverse chemical reactions were judged to affect consequences in three basic ways: 1) when the energy of the reaction is added to the energy of the detonator to make an explosive out of material that would not normally explode, 2) when the package pressurizes and a toxic gas or aerosolized liquid or solid is released, or when a reaction over pressurizes the package and the rupture of the package results in a fireball and an energy release that is greater than the equivalent of 100 pounds of TNT.

Table 1. Revised Threat-Based HM Classification Scheme

New Threat Grouping Name	HM Class/Division in Threat Groupings
Sensitive Explosives	Divisions 1.1, 1.2, 1.3
Reactive Chemicals	Divisions 1.4, 1.5, 1.6, some Class 3, Class 4, and Class 5 Materials
Flammable Gases	Division 2.1 Flammable Gases
Flammable Liquids	Class 3 Flammable Liquids
PIHs	Divisions 2.3 and 6.1 Hazard Zone A and B (PIH), Poisonous Gases and Liquids respectively
Infectious Materials	Division 6.2 Infectious Substances
High Activity Radioactives	Class 7 High Activity Radioactive Materials – > A2 quantities of normal form or A1 special form isotopes per package, includes Highway Route Controlled Quantities
Low Activity Radioactives	Class 7 Low Activity Radioactive Materials – commonly medical isotopes and wastes from nuclear reactors or from the processing of radioactive materials
Other HM	Division 6.1 other than Hazard Zone A and B, Class 8 Corrosives, Class 9 Miscellaneous HM, and Division 2.2 Non-flammable Gases

Based on this evaluation, it was found that adding a detonator to some Hazardous Class 3, 4 and 5 materials could result in mass detonation of the material. This assessment identified some examples of undesirable reactions involved a non-hazardous material, namely water. If water is added to cargo tanks containing Division 4.3 materials, the resultant reaction could pressurize and breach the cargo tank. Based on these studies, the revised threat based HM classification scheme was developed, as shown in Table 1. The threats believed to be the highest have been placed toward the top of the table.

CONSEQUENCE ASSESSMENT. Should the consequence be more severe for intentional acts? This question was addressed by first looking at the method used to analyze unintentional acts, i.e. transport accidents. The analysis then identified any differences for intentional acts. The starting point for addressing the consequences of unintentional acts was the amount of money the government would be willing to pay to avoid the occurrence of an injury or fatality. The values selected were taken from a published government source, (NHTSA, 1996) with an inflation factor applied to bring the value up to 2004. After inflation, the avoidance cost for a fatality became $3,000,000 and for an injury, $214,000. In Figure 1, seven other impact categories are shown. A cost study of actual hazardous material accidents (Battelle, 2001), that considered all the terms but business disruption, showed a common fatality/injury multiplier of 1.2 would include the other six impacts. Thus, if the fatality/impact from an unintentional worst case act was $300 million, based on 100 fatalities, the overall cost was estimated to be $360 million, ($300 times 1.2).

To estimate the fatality/injury multiplier for intentional acts, fires were considered a reasonable proxy. Large-scale hazardous materials incidents often include a fire and/or explosion, affecting multiple residences/businesses and resulting in community disruptions. A comprehensive fire impact cost study was recently completed in the United Kingdom, in which an estimate was made of the overall cost of fires on an annual basis in the country (UK, 2001). While this included costs associated with anticipation, consequence, and response, of interest to this study were the costs in the latter two categories, since the anticipation category relates to planning rather than contingent costs. In the analysis, the costs associated with consequence and response were further sub-divided into: 1) fatalities/injuries, 2) property loss, 3) fire service response, and 4) business loss. The fire impact costs of interest are shown in Table 2, along with the results of related studies performed in 1993 and 1999, respectively. The results of the fire study indicate a ratio of the total cost to the fatality/injury cost of approximately 3.0. This multiplier was adopted in this analysis as the fatality/injury multiplier for economic consequences associated with intentional acts.

Table 2. A Comparison of Fire Impact Costs by Category

	Fire Impact Costs		
Fire Impact Category	2001 Study	1999 Study	1993 Study
Fatalities/Injuries	1,070 (30%)	1,124 (29%)	1,206 (37%)
Property Loss	1,420 (40%)	1,119 (29%)	850 (26%)
Response Cost	1,020 (29%)	1,312 (34%)	1,018 (31%)
Business Loss	40 (1%)	296 (8%)	216 (7%)
TOTAL	3,550	3,851	3,290
Fatality/Injury Multiplier	3.32	3.43	2.73

Thus for any intentional or unintentional acts being considered, the first step is to estimate the number of injuries and fatalities and then for unintentional acts, type 1 and 2 impacts, multiply the avoidance cost for injuries and fatalities by 1.2 and for type 3 and 4 impacts, by a multiplier of 3.

BUSINESS DISRUPTION. In a recently completed study on the economic costs of natural disasters performed in Australia (Australia 2001), it was found that while there may be a significant economic impact due to business disruption on local businesses where a disaster occurs, a nation as a whole does not suffer a measurable effect. The reasoning is that the loss of supply from disaster-affected businesses will be offset by an increase in demand for similar goods from other businesses, as well as in the demand for disaster-relief supplies (e.g., rebuilding activity following the disaster stimulates the construction industry). Based on this finding that the net economic impact of such disruptions is typically small, no adjustment to the fatality/injury multiplier was made.

ASSESSMENT RESULTS

The consequence assessment methodology described in the previous subsections was applied to each HM class for the purpose of estimating the economic impacts for unintentional and intentional releases. With the exception of the typical unintentional release category, that are based on actual accident consequences, the results are considered order of magnitude estimates. Moreover, as a reminder, while these scenarios are believed to be reasonable, no determination has been made to assess their likelihood. Other scenarios with lower consequences might be more likely to be selected by a terrorist.

In reviewing these results, the following observations can be made:

- The economic impacts increase as release scenarios move from accidents to intentional acts.
- With the exception of radioactive materials incidents, directed releases result in far more serious economic impact than undirected releases. For radioactive material incidents, cleanup costs dominate and are similar for both intentional and unintentional acts.
- The economic impact of safety (accident) and security (intentional act) based releases lead to a different rank ordering of most severe HM categories. In particular, the economic impacts associated with accidents involving flammable and radioactive materials present relatively greater concerns in safety scenarios, with the opposite being true for infectious materials.
- The estimated impacts associated with worst case unintentional and intentional acts suggest that efforts to prevent (rather than manage) these impacts from being realized will have the greatest benefit.
- The impacts for the reasonable worst-case scenarios for both the low and high-activity radioactive material (RAM) are similar. High-activity RAM is shipped in accident resistant packaging reducing the fraction of the total inventory that is released in a severe accident. Such releases, if they do occur, are less severe, thereby lessening the potential consequences. Incidents involving shipments of low-activity RAM are more likely to release a larger fraction of their inventory, but since the total quantity of radioactive material is less, the quantity released and therefore the consequences are closer to the consequences for high-activity RAM.

FINDINGS AND IMPLICATIONS

A new paradigm has been introduced in which both safety and security risks can be evaluated as a systematic, integrated process. This new paradigm should enable risk managers, including regulators, to recognize the full impact of safety and security risk on a specific operation and allow one to understand the tradeoffs associated with the allocation of resources across safety and security initiatives. The methodology developed to reflect this resulted in the creation of a new logic flow diagram for representative safety and security risks, a revised (threat based) HM classification scheme and a technique for estimating the economic impacts of "reasonable" worst case scenarios for unintentional and intentional releases

Several areas of improvement have been identified that serve as opportunities for further research. First, more reliable data is needed to identify the number of shipments and shipment weights for HM highway transport in both bulk and non-bulk configurations. While commodity flow surveys have been performed (BOC, 2000), more detailed flow data is needed for each of the major HM threat-based groupings. Second, additional methodological work is needed to more effectively establish multipliers for incidents involving infectious and radioactive materials. Data describing impacts for both of these incident types is currently limited.

PROBABILITY OF INTENTIONAL ACTS. While not done in this study, because its purpose was to develop a workable methodology, the above paragraphs have shown that intentional and unintentional acts can be assigned reasonable consequences and it has also been shown how many of the branches in the event trees can be quantified. The one branch that is can not be quantified is the probability that the event is intentional as opposed to unintentional. It is clear the unintentional part of the probability term can be quantified because the annual frequency of accidents involving hazardous materials can be estimated. Since there is no historical basis for assigning an event frequency for an intentional event, the branch probability for an intentional act cannot be directly determined. An approach that could be taken is to estimate the probabilities for all the other branches and the consequences for all the paths for both intentional and unintentional and then work backwards to determine a branch probability at which the risk of intentional and unintentional acts are equal. Is this were done for all classes of hazardous material, the material with the lowest branch probability should be provided with more of the limited detection and/or prevention resources. Moreover, standard sensitivity analysis tools could also be used to rank the relative importance of each branch probability. This approach would enable officials to both estimate the cost effectiveness of various deterrence and preventative tools and techniques, as well as rank them in terms of cost/benefit ratio for the various classes of hazardous material shipments.

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