Risk of Multiple Small-Package Spills of Hazardous Substances

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ABSTRACT

The Materials Transportation Bureau (MTB) and U.S. Environmental Protection Agency (EPA) have agreed to regulate the transportation of hazardous substances only when they are shipped in larger than reportable quantities. This agreement simplifies the transportation regulations associated with hazardous substances and reduces the cost of complying with those regulations. However, it presents a potential risk of multiple small-package spills. A method is developed for assessing this spill risk by using data available from the Hazardous Material Incident Reporting System. Application of the data and methods revealed that the risk from multiple small-package spills was less than 0.5 percent of the risk of other regulated spills. Thus, the decision by EPA and MTB to regulate the transport of hazardous substances only when shipped in larger than reportable quantities is supported.

Section 311 of the Clean Water Act (CWA, Public Law 95-217) establishes a program for regulating hazardous substances. [CWA amends the Federal Water Pollution Control Act of 1972 (Public Law 92-500).] Pursuant to this legislation, 297 substances were designated as hazardous by the U.S. Environmental Protection Agency (EPA). These 297 substances were categorized into five groups based on their aquatic toxicity, and each group was assigned a reportable quantity (RQ). The groups and associated RQs are as follows: X, 1 lb; A, 10 lb; B, 100 lb; C, 1,000 lb; and D, 5,000 lb.

In cooperation with EPA, the Materials Transportation Bureau (MTB) of the U.S. Department of Transportation (DOT) incorporated these substances into its Hazardous Materials Table (49 C.F.R. 172.101). [For an excellent presentation of the regulations governing the transportation of hazardous materials, see Red Book on Transportation of Hazardous Materials (1).] Of the 297 substances, approximately 45 percent were already on the table by name. An additional 15 percent were already covered in general categories but not otherwise specified. The remaining 40 percent had not been previously covered. The Hazardous Materials Table has about 360 entries to cover the 297 substances, because many substances have different hazard classes or packing requirements or both, depending on the concentration and form. [For example, aldrin has six entries: aldrin, poison-B; aldrin, cast solid, ORM-A; aldrin mixture, dry (>65 percent aldrin), poison-B; aldrin mixture, dry (≤65 percent aldrin), ORM-A; aldrin mix ture, liquid (>60 percent aldrin), poison-B; aldrin mixture, liquid (≤60 percent aldrin), ORM-A.]

The MTB regulations on the transportation of hazardous substances require packages to be marked with the letters RQ when the package contains a reportable quantity or more of a hazardous substance. Packages containing less than a reportable quantity are not considered hazardous substances by MTB. (Note that they still fall under the regulation of CWA, however.) Further, the MTB requires reporting to the U.S. Coast Guard's National Response Center (NRC) when an RQ of a hazardous substance spills from a single package or, for bulk shipments, from a single transport vehicle.

These regulations present two categories of risk: First, a carrier could be involved in an incident in which many small unmarked packages spill and be unaware of the hazard because the packages were unmarked, and, second, multiple spills from marked packages could be unreported to the NRC because no single package spilled more than an RQ. The objective of this study is to assess these risks for X, A, and B hazardous substances where the chances of multiple shipments in a single vehicle are highest. The main source of data for the study is the MTB's Hazardous Material Incident Reporting (HMIR) System.

PROBLEM STATEMENT

The probability of a hazardous substance spill relative to the probability of a spill of a hazardous material is not a particularly meaningful estimate of relative risk for two reasons. First, not all hazardous substances are included in the commodity-specific HMIR data that have been extracted for analysis in this study. So the estimates of relative spill frequency from the HMIR data are likely to be inaccurate. Second, and most important, the damages that result from a spill of a hazardous material may be quite different from the damages from a hazardous substance spill. Risk should measure the expected hazard or damage. Expected hazard is the probability of the event multiplied by its severity or hazard level (2). So relative probability is a good measure of relative risk only when the damages from the events being compared are the same. For example, at the absurd level, if water were a hazardous material, it would greatly inflate the number of hazardous material spill reports and would dwarf the number of other spills in the file, but because the damage from a water spill is so slight compared with spills of hazardous substances like aldrin or parathion, the relative probability alone would be meaningless as a measure of relative risk. A more relevant example is wet electric storage batteries and paint when shipped in packages of less than 5 gal. These materials accounted for a large share of the spill reports, but after January 1, 1981, spills of these materials did not need to be reported to MTB.

With the foregoing points in mind, it has been decided to estimate the fraction of all hazardous substance spill incidents in which an RQ or more spills from multiple small unmarked packages. In this section, "small unmarked" and "unmarked" mean too small to require marking pursuant to the DOT-MTB regulations. Stated slightly differently, given that a spill incident involving an X, A, or B hazardous substance has occurred, what is the probability that an RQ has spilled from more than one small unmarked package?

There are two important characteristics of this approach that are worth noting:

1. The events whose probabilities are being compared (X, A, or B spill versus two or more small-package spills of X, A, or B substances) have similar consequences (note that because spill size is not the same, even this formulation of the problem does not completely reduce relative probabilities to relative risk).
2. The incomplete reporting to HMIR should not bias the measure of the relationship between spills of a collection of substances and multiple small-package spills of those substances. [Another approach to the analysis of risk in hazardous materials transportation is given in a report by Abkowitz et al. (3).]

The relative probability being estimated is the sum of (a) the probability that an RQ spills in an incident involving exactly two spills of the same X, A, or B substance; plus (b) the probability that an RQ spills in an incident involving three spills, two or more of the same X, A, or B substance; plus (c) the probability in four-spill incidents; and so on. The approach is to estimate the probability for two-spill incidents, then for three-spill incidents, and so on until the additions appear to be small enough to ignore.

For the two-spill case, the probability to be estimated is the probability that an incident occurs involving exactly two spills of the same hazardous substance where each of the two spilled packages contains less than an RQ but where the combined spill exceeds an RQ, given that an incident involving an X, A, or B hazardous substance spill has occurred. This probability can be stated precisely as follows:

$$P^{(2)} = \sum_{Y \epsilon S} \Pr(t = 2, k_1 = Y, k_2 = Y, w_1 < RQ_Y, w_2 < RQ_Y, Q_1 + Q_2 \geqslant RQ_Y \mid t \geqslant 1, k_1 \text{ or } k_2 \,\epsilon\, S) \quad (1)$$

where

- S = set of X, A, or B hazardous substances;
- $Y \,\epsilon\, S$ = Y is an element of S;
- k_1 = first spilled substance;
- k_2 = second spilled substance;
- t = number of packages spilled in the incident;
- w_1 = weight of the first spilled package;
- w_2 = weight of the second spilled package;
- Q_1 = weight spilled from the first package;
- Q_2 = weight spilled from the second package;
- RQ_Y = reportable quantity for substance Y; and
- $P^{(I)}$ = probability that an RQ of an X, A, or B hazardous substance spilled from unmarked packages in an incident involving exactly I spilled packages given that an incident involving an X, A, or B hazardous substance has occurred.

The HMIR data contain information on all these variables. So one approach would be to identify all incidents involving X, A, or B hazardous substances and then to identify the subset of incidents that meets the conditions specified in Equation 1. The relative frequency could be used as a measure of the relative probability. Unfortunately, there are only 1,531 X, A, or B hazardous substance spills in the HMIR data base covering 42 of the 92 hazardous substances covered by the CWA, too few to reliably measure the relative probability.

The approach taken to estimate $P^{(2)}$ is to reformulate Equation 1 into a set of factors that can be estimated from the data on hazardous material spill incidents by making some conservative approximations and some explicit assumptions. (There are 79,700 hazardous material spill incidents that were reported in the HMIR between January 1976 and August 1981, the period covered by the HMIR data used in this study.) This development is presented in the Appendix. The factors result from the definition of conditional probability (4) and from manipulations of the following form:

$$\Pr(A,B,C) = \Pr(A,B \mid C)\Pr(C) = \Pr(A \mid B,C)\Pr(B \mid C)\Pr(C)$$

The following five assumptions were used to reformulate Equation 1:

Assumption 1

$$\Pr(t = 2 \mid t \geqslant 1, k_1 = Y) = \Pr(t = 2 \mid t \geqslant 1)$$

Assumption 2

$$\Pr(k_2 = Y \mid t = 2, k_1 = Y) = \Pr(k_2 = k_1 \mid t = 2)$$

Assumption 3

$$\Pr(w_1 < 1 \mid t = 2, k_1 = Y, k_2 = Y) = \Pr(w_1 < 1 \mid t = 2)$$

Assumption 4

$$\Pr(w_2 < 1 \mid t = 2, k_1 = Y, k_2 = Y, w_1 < 1) = \Pr(w_2 < 1 \mid t = 2, k_1 = k_2, w_1 < 1)$$

Assumption 5

$$\Pr(Q_1 \geqslant 1/2 \text{ or } Q_2 \geqslant 1/2 \mid t = 2, k_1 = Y, k_2 = Y, w_1 < 1, w_2 < 1) = \Pr(Q_1 \geqslant 1/2 \text{ or } Q_2 \geqslant 1/2 \mid t = 2, w_1 < 1, w_2 < 1)$$

Equation 1 is then reformulated as follows:

$$\begin{aligned} P^{(2)} = {} & \Pr(t = 2 \mid t \geqslant 1)\Pr(k_2 = k_1 \mid t = 2) \\ & \times \Big(\Pr(k_1 \,\epsilon\, S_X \mid t \geqslant 1, k_1 \,\epsilon\, S)\Pr(w_1 < 1 \mid t = 2) \\ & \times \Pr(w_2 < 1 \mid t = 2, k_1 = k_2, w_1 < 1) \\ & \times \{1 - [\Pr(Q < 1/2 \mid t = 2, w < 1)]^2\} \\ & + \Pr(k_1 \,\epsilon\, S_A \mid t \geqslant 1, k_1 \,\epsilon\, S)\Pr(w_1 < 10 \mid t = 2) \\ & \times \Pr(w_2 < 10 \mid t = 2, k_1 = k_2, w_1 < 10) \\ & \times \{1 - [\Pr(Q < 5 \mid t = 2, w < 10)]^2\} \\ & + \Pr(k_1 \,\epsilon\, S_B \mid t \geqslant 1, k_1 \,\epsilon\, S)\Pr(w_1 < 100 \mid t = 2) \\ & \times \Pr(w_2 < 100 \mid t = 2, k_1 = k_2, w_1 < 100) \\ & \times \{1 - [\Pr(Q < 50 \mid t = 2, w < 100)]^2\}\Big) \end{aligned} \quad (2)$$

All of the assumptions involve independence of a component factor to variation with the specific substance considered. Note that assumptions 3, 4, and 5 depend on RQ and that only assumptions for X substances are shown. Similar expressions can be found in Equation 2 for A and B substances.

The first assumption states that the probability of a two-spill incident is independent of the material spilled. The second assumption states that the probability that the second material spilled in a two-spill incident is the same as the first material spilled is independent of the material spilled. The third assumption states that the probability that the first package spilled contained less than 1 lb (for X hazardous substances) is independent of the material in the shipment and of whether the two spilled materials are the same. The fourth assumption states that the probability that the second package spilled contains less than 1 lb (for X hazardous substances) is independent of the material spilled. Finally, the fifth assumption states that the probability that either spill is less than 1/2 lb (for X hazardous substances) is independent of the material spilled or the fact that the same material spilled from both packages.

In addition to these five assumptions, a conservative approximation was also used in the development of Equation 2. This approximation involves the probability that the sum of the two spills (Q_1 and Q_2) will exceed an RQ. Obviously either Q_1 or Q_2 must exceed 1/2 RQ if the sum is to exceed an RQ, but one could exceed 1/2 RQ while the sum was less than an RQ. The conservative approximation is as follows:

$$\Pr(Q_1 + Q_2 \geq RQ) = \Pr(Q_1 \geq 1/2\ RQ \text{ or } Q_2 \geq 1/2\ RQ)$$

The probability that the sum of the spills exceeds an RQ is approximated by the probability that one of the two spills exceeds 1/2 RQ. This is taken further in Equation 2 where the probability that one of the spills exceeds 1/2 RQ is replaced by 1 minus the probability that both spills are less than 1/2 RQ.

MEASURING THE FACTORS

Evidence of the validity of assumptions 1-5 will be presented later, but first the measures used to estimate each factor must be defined. The measures used for the factor probabilities in Equation 2 are as follows (similar measures are developed for A and B substances):

$$\Pr(t = 2 \mid t \geq 1) \cong (R_2/2)/[R_1 + (R_2/2) + (R_3/3)] \quad (3)$$

$$\Pr(k_2 = k_1 \mid t = 2) \cong R_{22}/R_2 \quad (4)$$

$$\Pr(w_1 < 1 \mid t \geq 1) \cong S_1/(R_1 + R_2 + R_3) \quad (5)$$

$$\Pr(w_2 < 1 \mid t = 2, k_1 = k_2, w_1 < 1) \cong G_1/H_1 \quad (6)$$

$$\Pr(Q_1 \geq 1/2 \text{ or } Q_2 \geq 1/2 \mid t = 2, w_1 < 1, w_2 < 1) \cong 1 - [\Pr(Q < 1/2 \mid t \geq 1, w < 1)]^2 \cong 1 - (F_1/S_1)^2 \quad (7)$$

$$\Pr(k_1 \in S_x \mid t \geq 1, k_1 \in S) \cong X/(X + A + B) \quad (8)$$

where

- R_1 = number of one-spill incident records (one record per incident),
- R_2 = number of two-spill incident records (two records per incident),
- R_3 = number of three-spill incident records (three records per incident),
- R_{22} = number of two-spill incident records where the same material spills in both records,
- S_1 = number of records where the shipment weight is less than 1 lb,
- G_1 = number of records where the same material spilled in a two-spill incident and where both spills were from packages with a shipment weight of less than 1 lb,
- H_1 = number of records that have shipment weights of less than 1 lb where the same material spilled in a two-spill incident,
- F_1 = number of records where the shipment weight is less than 1 lb and less than half of the shipment spilled, and
- X = number of category-X hazardous substance records.

Note that for each factor probability the numbers are defined over the set of spill records for which all necessary data were available. This permitted the largest sample of spills to be used in calculating each factor, but as a result the variables used are not precisely the same in each measure. For example, the R_1 used in estimating $\Pr(t = 2 \mid t > 1)$ is somewhat different from the R_1 used in estimating $\Pr(w < 1 \mid t \geq 1)$ because S_1 is not available for all spill records.

A conservative assumption has been introduced into the measurement of the probability that 1/2 RQ spills from one of the packages. Note in the definition of F_1 that instead of a 1/2 RQ spill a half shipment spill is used. This is equivalent to assuming that all shipments of less than an RQ contain exactly an RQ.

The variables used to measure the factor probabilities can be accumulated over a variety of sets of spill records. The largest set is the set of all hazardous material spills. The set of all hazardous substance spills is much smaller but also of interest. Further, the measures can be calculated for individual materials to examine how the estimates of the factor probabilities vary with material. This is a way of qualitatively testing the key assumption of independence of material that was used to develop Equation 2. Obviously, the smaller the sample the more the factor probability estimates will be influenced by the random noise or sampling error in the sample.

Table 1 presents estimates of the factor probabilities. Four estimates are presented. The first two are averages over all hazardous material and hazardous substance spill incidents. The next two estimates are selected from the commodity-specific factors. In the median estimate 50 percent of the commodities have factors of smaller size and 50 percent have factors of larger size. In the 90th-percentile case, 90 percent of the commodities have factors of smaller size and only 10 percent have larger factors. In these last two sets of estimates each estimate is selected separately, so different commodities are used for each factor. If a factor probability is nearly constant over the four columns, as in the case of the first factor, the corresponding assumption is supported. If the factor is not constant over the columns, the assumption is more doubtful, although at least part of the variation is caused by random noise or sampling error.

The similarities between the estimates of the factors calculated over all hazardous substance incidents and over all hazardous material incidents suggest that, in aggregate, spill incidents involving hazardous substances and hazardous materials are similar. In percentage terms, the largest discrepancies arise in factors involving shipment size $[\Pr(w_1 < RQ \mid t \geq 1)]$. The dominance of anhydrous ammonia in the hazardous substance incidents probably accounts for the discrepancy, because it is transported in large shipments.

The similarities between the average and median estimates for the hazardous materials indicate that a few unusual hazardous materials are not dominating the spill data. The 90th-percentile estimates give an indication of the range of factor values that can be expected. As mentioned earlier, some of the differences between the median and 90th-percentile estimates are due to random noise or sampling error, which results from the small number of spills over which the factors are calculated. Some of the difference is undoubtedly due to real differences in the way specific materials are shipped and their susceptibility in spill incidents.

RESULTS

The factor probabilities can be used in Equation 2

TABLE 1 Estimates of the Factor Probabilities

Measure	Factor Estimate: Avg for All X, A, or B Hazardous Substance Spill Incidents	For All Hazardous Material Spill Incidents: Avg	Median	90th Percentile
$Pr(t = 2 \mid t \geq 1)$	0.0406[a]	0.0606[b]	0.0605[c]	0.0804[c]
$Pr(k_2 = k_1 \mid t = 2)$	0.4870[a]	0.3886[b]	0.2917[c]	0.7225[c]
$Pr(w_1 < 1 \mid t \geq 1)$	0.0000[d]	0.0009[e]	0.0000[c]	0.0024[c]
$Pr(w_2 < 1 \mid t = 2, k_1 = k_2, w_1 < 1)$	1.000[f]	1.000[f]	1.000[f]	1.000[f]
$1 - [Pr(Q < 1/2 \mid t \geq 1, w < 1)]^2$	1.000[f]	0.9600[g]	1.000[f]	1.000[c]
$Pr(w_1 < 10 \mid t \geq 1)$	0.0198[d]	0.0315[e]	0.0234[c]	0.1121[c]
$Pr(w_2 < 10 \mid t = 2, k_1 = k_2, w_1 < 10)$	1.000[f]	0.5385[e]	1.000[f]	1.000[f]
$1 - [Pr(Q < 5 \mid t \geq 1, w < 10)]^2$	0.8457[d]	0.8209[e]	0.7934[c]	1.000[c]
$Pr(w_1 < 100 \mid t \geq 1)$	0.0989[b]	0.1547[e]	0.1383[c]	0.3578[c]
$Pr(w_2 < 100 \mid t = 2, k_1 = k_2, w_1 < 100)$	1.000[f]	0.6531[e]	0.5106[g]	1.000[g]
$1 - [Pr(Q < 50 \mid t \geq 1, w < 100)]^2$	0.3485[d]	0.4813[e]	0.4861[c]	0.7256[c]

[a]Calculated over the 1,416 X, A, or B hazardous substance spill incidents.
[b]Calculated over the 79,700 hazardous material spill incidents.
[c]Measured over the 72 materials with more than 100 incidents.
[d]Calculated over the 1,145 X, A, or B hazardous substance spill incidents with good spill and shipment size data.
[e]Calculated over the 44,699 hazardous material spill incidents with good spill and shipment size data.
[f]Sample did not contain adequate information. Upper bound of 1.0 used.
[g]Measured over the 31 materials with more than 10 matching-material, two-spill incidents.

along with the portion of all X, A, or B hazardous substance spills that belongs to each category $[Pr(k_1 \in S_X \mid k_1 \in S)]$ to estimate $P^{(2)}$. Table 2 gives these estimates of $P^{(2)}$ along with estimates of the probability that a multiple-small-package incident releases an RQ, given an X, an A, or a B hazardous substance spill. For the first three sets of factor estimates the estimates of $P^{(2)}$ are similar. $P^{(2)}$ given an X hazardous substance spill is the only exception. The extremely low frequency of shipments weighing less than 1 lb resulted in no observations in the average hazardous substance sample and none for the median hazardous material either. All other estimates are quite close, within a factor of 2. These results again suggest that using the average hazardous material factors produces reasonable estimates of hazardous substance spill probabilities. In the remainder of the paper, the focus will be on the analysis of probability estimates developed from the average factors calculated from the set of all hazardous material spills.

The 90th-percentile factor estimates produce estimates of $P^{(2)}$ that are substantially higher than the other three estimates. The 90th-percentile factor estimates should be interpreted as estimates of the range of the commodity-specific spill probabilities that are consistent with the average estimate. Table 3 shows the same 90th-percentile estimates of $P^{(2)}$ as in Table 2 but also shows the highest estimates of $P^{(2)}$ developed for single materials. These estimates are developed from the factors for a single material. Ammonium hydroxide has the highest $P^{(2)}$ of all hazardous materials, which is about the same as the 90th-percentile estimate. This is a little misleading, however, because 1.0 was used as the factor $[Pr(w_2 < RQ \mid t = 2, k_1 = k_2, w_1 < RQ)]$ for all materials because most of the single-material samples were too small to estimate this factor. Calcium hypochlorite is the X, A, or B hazardous substance with the highest estimate of $P^{(2)}$.

The estimates of $P^{(2)}$ in Table 2 suggest that the probability of an RQ spill from more than one unmarked package is small (10^{-3}). However, the probability of three, four, and more spills must be added to the estimates of $P^{(2)}$ to obtain the full probability. $P^{(3)}$ and $P^{(4)}$ cannot be ignored a priori because there are two factors that change in different directions and influence the probability

TABLE 2 Probability of RQ Spills from Two-Spill Incidents

Factor Estimate	$P^{(2)}$, Probability That an RQ Spills from Two Unmarked Packages Given: X Spill	A Spill	B Spill	Spill of Some X, A, or B Substance
Avg for all hazardous substance spill incidents	0.0	3.3×10^{-4}	6.8×10^{-4}	5.7×10^{-4}
For all hazardous material spill incidents				
Avg	2.0×10^{-5}	3.3×10^{-4}	1.1×10^{-3}	9.3×10^{-4}
Median	0.0	3.3×10^{-4}	6.1×10^{-4}	5.1×10^{-4}
90th percentile	1.4×10^{-4}	6.5×10^{-3}	1.5×10^{-2}	1.2×10^{-2}

TABLE 3 Possible Variations in Probability with Material

Factor Estimate	$P^{(2)}$, Probability That an RQ Spills from Two Unmarked Packages Given: X Spill	A Spill	B Spill	Spill of Some X, A, or B Substance
90th percentile[a]	1.4×10^{-4}	6.5×10^{-3}	1.5×10^{-2}	1.2×10^{-2}
Highest single hazardous material (ammonium hydroxide, < 45 percent ammonia)				1.1×10^{-2}
Highest single X, A, or B hazardous substance (calcium hypochlorite mixture)				1.2×10^{-3}

[a]Each factor used in calculating the probability was chosen so that 90 percent of the hazardous materials had factors with lower values.

of a larger number of spills. First, incidents with more spills are much rarer than two-spill incidents. However, when more packages spill, an RQ spill is more likely to result. Table 4 presents the contributions of two-, three-, and four-spill incidents to the total estimated probability that a hazardous substance spill will be an RQ spill from more than one unmarked package. The factors used to calculate these probabilities are presented in a study by Hoxie and Woodman (5).

TABLE 4 Contribution of Number of Spills

	Probability That an RQ Spills from More Than One Unmarked Package Given			
$p^{(i)a}$	X Spill	A Spill	B Spill	Spill of Some X, A, or B Substance
$p^{(2)}$	2.0×10^{-5}	3.3×10^{-4}	1.1×10^{-3}	9.3×10^{-4}
$p^{(3)}$	3.1×10^{-6}	5.3×10^{-5}	2.1×10^{-4}	1.7×10^{-4}
$p^{(4)}$	8.6×10^{-7}	1.5×10^{-5}	6.7×10^{-5}	5.4×10^{-5}
Total	2.4×10^{-5}	4.0×10^{-4}	1.4×10^{-3}	1.2×10^{-3}

[a]Averaged over all hazardous material spills.

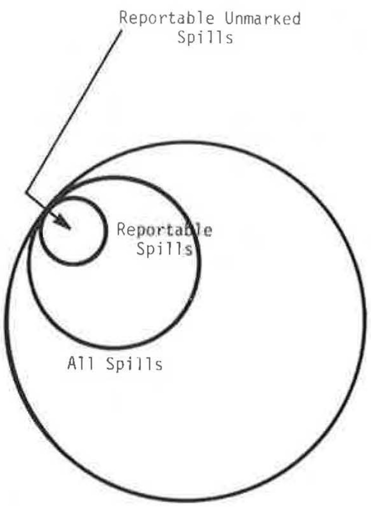
As the data in Table 4 indicate, three- and four-spill incidents add only about 30 percent to the $P^{(2)}$ estimate, and the contribution drops off by about a factor of 5 with each increase of 1 in the number of packages spilled in the incident. Incidents of five spills or more can safely be ignored.

The total probability (1.2×10^{-3}) is very small. The 42 X, A, or B hazardous substances reported in the HMIR were involved in 1,531 spills over the period January 1976 through August 1981. Over this 5.5-year period, then, it would be expected that there would be roughly two spills of an RQ from multiple-spill incidents involving unmarked packages of these 42 hazardous substances. Actually, none were reported.

Only half of the X, A, or B hazardous substances designated under the CWA are in the HMIR data, and without knowledge of the total spills of the unreported half, an estimate of the total number of RQ spills from unmarked packages cannot be made. Further, new designations of hazardous substances by EPA under the Comprehensive Environmental Response, Compensation and Liability Act of 1980 (CERCLA) (Public Law 96-510) will also increase the number of X, A, or B hazardous substance spills. With the increases in hazardous substance spills, the expected number of RQ spills from unmarked packages will increase in a ratio of about 800 to 1; that is, of every 800 hazardous substance spills, one is expected to be an RQ spill from small unmarked packages. As the proportion of X, A, or B hazardous substance spills that falls into each category changes from the 0.1109X, 0.1135A, or 0.7756B found in the HMIR data, the expected rate of increase in RQ spills from unmarked packages will also vary. The 1.2×10^{-3} estimate is $(0.1109 \times 2.4 \times 10^{-5}) + (0.1135 \times 4.0 \times 10^{-4}) + (0.7756 \times 1.4 \times 10^{-3})$; $1.2/1{,}000 \approx 1/800$.

OTHER MEASURES

Without being able to estimate the total number of RQ spills from unmarked packages, an important statistic in attempting to judge the acceptability of these spill probabilities is the fraction of reportable incidents that would go unreported because the spill came from more than one unmarked package. ("Reportable" means spills of more than an RQ. The regulations currently require reporting to the NRC only when an RQ spills from a single package.) This fraction is different from the 1.2×10^{-3} cited earlier because not all hazardous substance incidents result in spills of an RQ. In fact, only 0.266 of the incidents spill more than 100 lb, 0.533 spill more than 10 lb, and 0.898 spill more than 1 lb. (These values are calculated over all spill reports in the HMIR data and cover all hazardous materials.) The foregoing values are used with the probabilities in Table 4 to calculate the fraction of reportable incidents that would go unreported because the spills were from unmarked packages. Figure 1 shows these relationships for B hazardous substances and the following tabulation gives the results for X, A, and B hazardous substances:



1. $\frac{\text{Reportable}}{\text{All}} = .27$

2. $\frac{\text{Reportable, Unmarked}}{\text{All}} = 1.4 \times 10^{-3}$

3. $\frac{\text{Reportable, Unmarked}}{\text{Reportable}} = \frac{1.4 \times 10}{.27} = 5.3 \times 10^{-3}$

FIGURE 1 Relationship among all spills, reportable spills, and reportable spills from unmarked packages for B hazardous substance.

	Probability That an RQ Spills from More Than One Unmarked Package Given an RQ Spill of		
	X	A	B
Avg over all spills	2.7×10^{-5} (1 in 37,000)	7.5×10^{-4} (1 in 1,300)	5.3×10^{-3} (1 in 190)

Roughly 1 in 37,000 reportable X hazardous substance spills, 15 in 20,000 reportable A hazardous substance incidents, and 5 in 1,000 reportable B hazardous substance incidents would be from unmarked packages. All of these fractions are small and are probably much smaller than the fraction of incidents that are not reported for other reasons.

One of the reasons for nonreporting could be that a spill of less than an RQ from a marked package is added to a spill from an unmarked package. In this case the operator of the vehicle would know that a hazardous substance had spilled but he would be unaware that an RQ had spilled. Table 5 presents estimates of the fraction of reportable spills that results from spills of less than an RQ from a marked

TABLE 5 Fraction of Reportable Two-Spill Incidents That Might Not Be Reported Because No Single Package Spilled an RQ

Type of Two-Spill Incident[a]	Fraction of X Spills	A Spills	B Spills
One marked and one unmarked package	2.4×10^{-6}	5.4×10^{-4}	3.6×10^{-3}
Two marked packages	2.7×10^{-3}	1.8×10^{-2}	2.1×10^{-2}
Total	2.7×10^{-3} (1 in 370)	1.9×10^{-2} (1 in 50)	2.1×10^{-2} (1 in 40)

[a]In which less than an RQ spills from each package but the sum of spills exceeds an RQ.

package and a spill from an unmarked package. These fractions are roughly the same size as the fraction of reportable spills from multiple spills of unmarked packages.

Table 5 also presents the fraction of reportable spills that are from multiple spills of marked packages where less than an RQ spills from each package. Under the MTB's regulations these incidents do not need to be reported even though an RQ spilled in the incident. This fraction is much larger than the fraction from a marked and an unmarked package or that from two unmarked packages. The factors used to calculate the fractions reported in Table 5 are given in the report by Hoxie and Woodman (5).

CONCLUSIONS

Table 6 shows estimates of the fraction of incidents in which an RQ or more spills for the two categories of risk. The estimates were derived from the MTB's HMIR data and the probability equation developed in the foregoing and in the report by Hoxie and Woodman (5). The results indicate that less than 0.53 percent of all B hazardous substance spills of an RQ or more are from incidents involving multiple spills from unmarked packages. Further, the comparable fraction is even smaller for A hazardous substances and smaller still for X hazardous substances.

TABLE 6 Summary of Multiple-Spill Risk

Type of Incident	Fraction of RQ Spills of X Substance	A Substance	B Substance
Unmarked and unreported (multiple[a] spills from unmarked packages)	2.7×10^{-5}	7.5×10^{-4}	5.3×10^{-3}
Unreported			
One spill of unmarked package and one spill of less than an RQ from a marked package	2.4×10^{-6}	5.4×10^{-4}	3.6×10^{-3}
Two spills of less than an RQ from marked packages	2.7×10^{-3}	1.8×10^{-2}	2.1×10^{-2}

[a]Includes incidents with two, three, and four spills.

The results are somewhat less complete for incidents spilling more than an RQ that are unreported because no single spill exceeds an RQ. Only two-spill incidents are included in the analysis, but the risk calculations indicate that such cases compose less than 3 percent of all incidents in which an RQ or more of B hazardous substance spills. Further, this fraction is dominated by the spills from marked packages, and because only the letters RQ are marked on the package, it seems likely that these spills would be reported (overreported) even though reporting is not required by current regulations. They would be reported because the marking does not indicate the category of hazardous substance or the RQ threshold, so as long as the package spilled more than 1 lb, it could potentially be an RQ.

These results are based on several assumptions. Because the probabilities were estimated from hazardous material spill data, the most important assumption is that hazardous substances are shipped and spill in ways that are the same as those for hazardous materials. An analysis of the spill data for the 42 X, A, or B hazardous substances contained in the HMIR data base supports the validity of this assumption. Other assumptions involve the independence of probability factors across substances and the degree to which the HMIR data are representative of all hazardous material spills.

APPENDIX

The objective of this Appendix is to show how assumptions 1-5 are used to develop an upper bound on the probability of an incident in which two packages containing the same hazardous substance spill when each package contains less than an RQ but more than an RQ spills, given that an incident involving a hazardous substance has occurred. Obviously another goal of the development is to reduce the probability to a set of probabilities each of which can be estimated by using the HMIR data.

The probability of interest $[P^{(2)}]$ is as follows:

$$P^{(2)} = \sum_{Y \in S} \Pr(t = 2, k_1 = Y, k_2 = Y, w_1 < RQ_y, w_2 < RQ_y, Q_1 + Q_2 \geq RQ_y \mid t \geq 1) / \sum_{Z \in S} \Pr(k_1 = Z \text{ or } k_2 = Z \mid t \geq 1) \quad (9)$$

where the symbols are as defined for Equation 1.

Examine the numerator:

$$C(Y) = \Pr(t = 2, k_1 = Y, k_2 = Y, w_1 < RQ_Y, w_2 < RQ_Y, Q_1 + Q_2 \geq RQ_Y \mid t \geq 1)$$

$$= \Pr(t = 2, k_2 = Y, w_1 < RQ_Y, w_2 < RQ_Y, Q_1 + Q_2 \geq RQ_Y \mid t \geq 1, k_1 = Y) \times \Pr(k_1 = Y \mid t \geq 1)$$

$$= \Pr(k_2 = Y, w_1 < RQ_Y, w_2 < RQ_Y, Q_1 + Q_2 \geq RQ_Y \mid t = 2, k_1 = Y) \times \Pr(t = 2 \mid t \geq 1, k_1 = Y) \times \Pr(k_1 = Y \mid t \geq 1) \quad (10)$$

Assume that the probability of a two-spill incident is independent of the material spilled (assumption 1). Then

$$C(Y) = \Pr(k_2 = Y, w_1 < RQ_Y, w_2 < RQ_Y, Q_1 + Q_2 \geq RQ_Y \mid t = 2, k_1 = Y) \times \Pr(t = 2 \mid t \geq 1) \times \Pr(k_1 = Y \mid t \geq 1) \quad (11)$$

$$C(Y) = \Pr(w_1 < RQ_Y, w_2 < RQ_Y, Q_1 + Q_2 \geq RQ_Y \mid t = 2, k_1 = Y, k_2 = Y) \times \Pr(k_2 = Y \mid t = 2, k_1 = Y) \times \Pr(t = 2 \mid t \geq 1) \times \Pr(k_1 = Y \mid t \geq 1) \quad (12)$$

Assume that the probability that the second material spilled in a two-spill incident is the same as the first material spilled is independent of the first material (assumption 2). Then

$$C(Y) = \Pr(w_1 < RQ_Y, w_2 < RQ_Y, Q_1 + Q_2 \geq RQ_Y \mid t = 2, k_1 = Y, k_2 = Y) \times \Pr(k_2 = k_1 \mid t = 2) \times \Pr(t = 2 \mid t \geq 1) \times \Pr(k_1 = Y \mid t \geq 1) \quad (13)$$

Recall that

$$P^{(2)} = \sum_{Y \epsilon S} C(Y) / \sum_{Z \epsilon S} \Pr(k_1 = Z \text{ or } k_2 = Z | t \geq 1)$$

$$= \sum_{Y \epsilon S} [\Pr(w_1 < RQ_Y, w_2 < RQ_Y, Q_1 + Q_2 \geq RQ_Y | t = 2, k_1 = Y, k_2 = Y) \times \Pr(k_2 = k_1 | t = 2) \times \Pr(t = 2 | t \geq 1) \times \Pr(k_1 = Y | t \geq 1)] \div \sum_{Z \epsilon S} \Pr(k_1 = Z \text{ or } k_2 = Z | t \geq 1) \quad (14)$$

This expression can be rewritten as follows:

$$P^{(2)} = \Pr(t = 2) | t \geq 1) \times \Pr(k_2 = k_1 | t = 2) \times \sum_{Y \epsilon S} [\Pr(k_1 = Y | t \geq 1) / \sum_{Z \epsilon S} \Pr(k_1 = Z \text{ or } k_2 = Z | t \geq 1)] \times \Pr(w_1 < RQ_Y, w_2 < RQ_Y, Q_1 + Q_2 \geq RQ_Y | t = 2, k_1 = Y, k_2 = Y) \quad (15)$$

The first two terms can be moved out of the summation because they are constant, unaffected by the material.

Examine the following:

$$D(Y) = \Pr(k_1 = Y | t \geq 1) / \sum_{Z \epsilon S} \Pr(k_1 = Z \text{ or } k_2 = Z | t \geq 1) \quad (16)$$

$\Pr(k_1 = Z$ or $k_2 = Z \mid t \geq 1)$ is short for $\Pr(t = 1$ and $k_1 = Z$; or $t = 2$ and $k_1 = Z$; or $t = 2$ and $k_2 = Z \mid t \geq 1)$. However, because $t = 2$ only 0.06 of the time that $t \geq 1$ and because $k_1 = Z$ some of the time when $k_2 = Z$, this expression can be approximated by $\Pr(k_1 = Z \mid t \geq 1)$. (This term should also cover the situation in which $t = 3, 4, \ldots$, and a complete statement of this approximation would include $k_3, k_4, \ldots = Z$. However, the arguments made when $t = 2$ apply for the $t = 3, 4, \ldots$ cases as well.) So

$$D(Y) = \Pr(k_1 = Y | t \geq 1) / \sum_{Z \epsilon S} \Pr(k_1 = Z | t \geq 1)$$

$$= \Pr(k_1 = Y | t \geq 1, Y \epsilon S) \quad (17)$$

Thus, the original probability becomes

$$P^{(2)} = \Pr(t = 2 | t \geq 1) \times \Pr(k_2 = k_1 | t = 2) \sum_{Y \epsilon S} \Pr(k_1 = Y | t \geq 1, Y \epsilon S) \times \Pr(w_1 < RQ_Y, w_2 < RQ_Y, Q_1 + Q_2 \geq RQ_Y | t = 2, k_1 = Y, k_2 = Y) \quad (18)$$

Now $S = S_X + S_A + S_B$, where S_X, S_A, and S_B are the subsets of X, A, or B hazardous substances and RQ_Y = 1 lb for $Y \epsilon S_X$, RQ_Y = 10 lb for $Y \epsilon S_A$, and RQ_Y = 100 lb for $Y \epsilon S_B$. So $P^{(2)}$ can be rewritten as follows:

$$P^{(2)} = \Pr(t = 2 | t \geq 1) \times \Pr(k_2 = k_1 | t = 2)[\sum_{Y \epsilon S_X} \Pr(k_1 = Y | t \geq 1, Y \epsilon S) \times \Pr(w_1 < 1, w_2 < 1, Q_1 + Q_2 \geq 1 | t = 2, k_1 = Y, k_2 = Y) + \sum_{Y \epsilon S_A} \Pr(k_1 = Y | t \geq 1, Y \epsilon S) \times \Pr(w_1 < 10, w_2 < 10, Q_1 + Q_2 \geq 10 | t = 2, k_1 = Y, k_2 = Y) + \sum_{Y \epsilon S_B} \Pr(k_1 = Y | t \geq 1, Y \epsilon S) \times \Pr(w_1 < 100, w_2 < 100, Q_1 + Q_2 \geq 100 | t = 2, k_1 = Y, k_2 = Y)] \quad (19)$$

Examine the second factor in the first sum in the brackets [call it F(Y)]:

$$F(Y) = \Pr(w_1 < 1, w_2 < 1, Q_1 + Q_2 \geq 1 | t = 2, k_1 = Y, k_2 = Y) \quad (20)$$

$$F(Y) = \Pr(w_2 < 1, Q_1 + Q_2 \geq 1 | t = 2, k_1 = Y, k_2 = Y, w_1 < 1) \times \Pr(w_1 < 1 | t = 2, k_1 = Y, k_2 = Y) \quad (21)$$

Assume that the probability that the first package spilled contained less than 1 lb is independent of the material in the shipment and of whether the two spilled materials are the same (assumption 3). Then

$$F(Y) = \Pr(w_2 < 1, Q_1 + Q_2 \geq 1 | t = 2, k_1 = Y, k_2 = Y, w_1 < 1) \times \Pr(w_1 < 1 | t = 2)$$

$$= \Pr(Q_1 + Q_2 \geq 1 | t = 2, k_1 = Y, k_2 = Y, w_1 < 1, w_2 < 1) \times \Pr(w_2 < 1 | t = 2, k_1 = Y, k_2 = Y, w_1 < 1) \times \Pr(w_1 < 1 | t = 2) \quad (22)$$

Assume that the probability that the second package spilled contains less than 1 lb is independent of the material spilled (assumption 4). Then

$$F(Y) = \Pr(Q_1 + Q_2 \geq 1 | t = 2, k_1 = Y, k_2 = Y, w_1 < 1, w_2 < 1) \times \Pr(w_2 < 1 | t = 2, k_1 = k_2, w_1 < 1) \times \Pr(w_1 < 1 | t = 2) \quad (23)$$

Examine the first factor of F(Y):

$$G(Y) = \Pr(Q_1 + Q_2 \geq 1 | t = 2, k_1 = Y, k_2 = Y, w_1 < 1, w_2 < 1) \quad (24)$$

Certainly either Q_1 or Q_2 must be larger than 1/2 lb if $Q_1 + Q_2$ is to be larger than a pound. So

$$G(Y) \leq H(Y) = \Pr(Q_1 \geq 1/2 \text{ or } Q_2 \geq 1/2 | t = 2, k_1 = Y, k_2 = Y, w_1 < 1, w_2 < 1) \quad (25)$$

Assume that the probability that either spill is less than 1/2 lb is independent of the material spilled or the fact that the same material spilled from both packages (assumption 5). Then

$$H(Y) = \Pr(Q_1 \geq 1/2 \text{ or } Q_2 \geq 1/2 | t = 2, w_1 < 1, w_2 < 1) \quad (26)$$

If it is assumed either that Q_1 is independent of Q_2 or that if it is not independent, they are positively associated, an estimate of an upper bound on H(Y) can be made:

$$H(Y) \leq 1 - [\Pr(Q \leq 1/2 | t = 2, w < 1)]^2 \quad (27)$$

(By positively associated it is meant that larger values of Q_1 are on the average associated with larger values of Q_2 and similarly smaller values of Q_1 are associated with smaller values of Q_2. By assuming that Q_1 and Q_2 are either positively associated or independent it is assumed that they are not negatively associated. That is, it is assumed that smaller values of Q_1 are not on the average associated with larger values of Q_2.) So

$$G(Y) \leq 1 - [\Pr(Q \leq 1/2 | t = 2, w < 1)]^2 \quad (28)$$

and an upper bound on F(Y) is

$$F(Y) = \{1 - [\Pr(Q \leq 1/2 | t = 2, w < 1)]^2\} \times \Pr(w_2 < 1 | t = 2, k_1 = k_2, w_1 < 1) \times \Pr(w_1 < 1 | t = 2) \quad (29)$$

Recall that the first summation in the last expression for $P^{(2)}$ is

$$J(Y) = \sum_{Y \epsilon S_X} \Pr(k_1 = Y | t \geq 1, Y \epsilon S) F(Y) \quad (30)$$

Substituting in the upper bound on F(Y) yields

$$J(Y) = \sum_{Y \epsilon S_X} \Pr(k_1 = Y | t \geq 1, Y \epsilon S) \times \Pr(w_2 < 1 | t = 2, k_1 = k_2, w_1 < 1) \times \Pr(w_1 < 1 | t = 2) \times \{1 - [\Pr(Q \leq 1/2 | t = 2, w < 1)]^2\} \quad (31)$$

Because only the first factor depends on the material, this expression can be rewritten as follows:

$$J(Y) = \Pr(w_2 < 1 | t = 2, k_1 = k_2, w_1 < 1) \times \Pr(w_1 < 1 | t = 2) \times \{1 - [\Pr(Q \leq 1/2 | t = 2, w < 1)]^2\} \times \sum_{Y \epsilon S_X} \Pr(k_1 = Y | t \geq 1, Y \epsilon S) \quad (32)$$

Now the final summation in J(Y) can be restated:

$$\sum_{Y \epsilon S_X} \Pr(k_1 = Y | t \geq 1, Y \epsilon S) = \Pr(k_1 \epsilon S_X | t \geq 1, k_1 \epsilon S) \quad (33)$$

and

$$J(Y) = \Pr(w_2 < 1 | t = 2, k_1 = k_2, w_1 < 1) \times \Pr(w_1 < 1 | t = 2) \times \{1 - [\Pr(Q \leq 1/2 | t = 2, w < 1)]^2\} \times \Pr(k_1 \epsilon S_X | t \geq 1, k_1 \epsilon S) \quad (34)$$

Similar logic can be used to develop upper bounds on the other two summations in the final expression for $P^{(2)}$. The result is

$$P^{(2)} = \Pr(t = 2 | t \geq 1) \times \Pr(k_2 = k_1 | t = 2) \times \Big(\Pr(k_1 \epsilon S_X | t \geq 1, k_1 \epsilon S) \times \Pr(w_1 < 1 | t = 2) \times \Pr(w_2 < 1 | t = 2, k_1 = k_2, w_1 < 1) \times \{1 - [\Pr(Q \leq 1/2 | t = 2, w < 1)]^2\} + \Pr(k_1 \epsilon S_A | t \geq 1, k_1 \epsilon S) \times \Pr(w_1 < 10 | t = 2) \times \Pr(w_2 < 10 | t = 2, k_1 = k_2, w_1 < 10) \times \{1 - [\Pr(Q \leq 5 | t = 2, w < 10)]^2\} + \Pr(k_1 \epsilon S_B | t \geq 1, k_1 \epsilon S) \times \Pr(w_1 < 100 | t = 2) \times \Pr(w_2 < 100 | t = 2, k_1 = k_2, w_1 < 100) \times \{1 - [\Pr(Q \leq 50 | t = 2, w < 100)]^2\}\Big) \quad (35)$$

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Estimating the Release Rates and Costs of Transporting Hazardous Waste

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ABSTRACT

In the United States more than 160 million metric tons of hazardous waste are generated annually, and there has been concern over the management of these wastes and their impact on the population and environment. Responding to this issue, policy makers have begun to examine the risks and costs associated with hazardous waste treatment, transport, and disposal. The focus of this paper is the expected releases and costs associated with the transportation of hazardous waste by truck. Expected release rates are derived for eight container classes that may be used in the transport of hazardous materials and waste. The results indicate that the expected fraction released per mile shipped ranges from approximately 10^{-8} to 10^{-6}, depending on the container class. Expected released fractions at terminal points range from 10^{-6} to 10^{-3}. Thus, the expected released fractions during transport are potentially as large as the corresponding released fractions at disposal sites and treatment facilities. A review is also conducted of previous studies of the cost of hazardous waste transport. Several deficiencies are noted, particularly assumptions related to shipment characteristics and the lack of a comparison of actual rates charged by waste haulers. To overcome these deficiencies, new formulas are derived for estimating the cost of waste transport by tanker and stake (flatbed) truck. Cost estimates based on these formulas are subsequently compared with quoted industry rates. A conclusion is reached that the revised procedure is representative and can be used in policy analysis.