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

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

and

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

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

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

ACKNOWLEDGMENT

This study was suggested and supported by the Office of Solid Waste and Emergency Response of EPA and the author is grateful to Jack Kooyoomjian and Barbara Hostage of that office for their encouragement. The author also wishes to thank Donna Woodman, Edwin Roberts, and Simon Prensky for their helpful suggestions and Peter Mengert for his help in the mathematical development of the relative risk measure.

REFERENCES

1. L.W. Bierlein. Red Book on Transportation of Hazardous Materials. Cahners Books International, Inc., Boston, Mass., 1977.
2. S. Salem, K. Solomon, and M. Yesley. Issues and Problems in Inferring a Level of Acceptable Risk. Report R-2561-DOE. Rand Corporation, Santa Monica, Calif., Aug. 1980.
3. M. Abkowitz, A. Eiger, and S. Srinivasan. Assessing the Risks and Costs of Transporting Hazardous Wastes. Status Report. Development Planning and Research Associates, Manhattan, Kans., n.d.
4. A. Drake. Fundamentals of Applied Probability Theory. McGraw-Hill, New York City, 1967.
5. P. Hoxie and D. Woodman. Risks of Hazardous Substance Spills from Unmarked Packages and Containers. Staff Study SS-223-US-65. Transportation Systems Center, U.S. Department of Transportation, Cambridge, Mass., Sept. 1982.

Estimating the Release Rates and Costs of Transporting Hazardous Waste

MARK ABKOWITZ, AMIR EIGER, and SURESH SRINIVASAN

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.

In the United States more than 160 million metric tons of hazardous waste are generated annually (1). In response to a growing concern over the management of these wastes and their impact on the population and environment, policy makers have begun to examine the risks and costs of treatment, transport, and disposal of hazardous waste.

The U.S. Environmental Protection Agency (EPA) has taken a leading role in assessing the trade-offs between various aspects of the disposal and treatment problem. In 1981 EPA's Office of Solid Waste began development under the Resource Conservation and Recovery Act (RCRA) of a Risk/Cost Analysis Model to assist in the development of regulations and standards for hazardous waste treatment, storage, and disposal facilities.

The RCRA Risk/Cost Analysis Model consists of an array of possible ways to treat and dispose of the hazardous wastes generated in the United States (2). Three main factors are considered in the model's formulation of possible ways to manage hazardous waste:

1. The type of waste (and its hazardous chemical constituents);
2. The types of technologies used to treat, transport, and dispose of the waste; and
3. The environmental settings in which the wastes are treated, transported, and disposed.

The model forms all possible combinations of a list of wastes, technologies, and environmental settings, or WET cells. It then calculates the risks and costs involved in each WET cell. In this fashion, the relative merits and drawbacks of various hazardous waste management strategies can be identified.

The focus in this paper is on the development of fraction release estimates for the transport technology component of the RCRA Risk/Cost Analysis Model. A secondary topic is the derivation of cost estimates of transporting hazardous waste. This includes a review of existing work directed at estimating the cost of transporting hazardous waste and modifications to existing methods based on hazardous waste shipment characteristics and current economic reasoning. The new cost formulas are subsequently compared with quoted industry rates to ascertain whether the revised approach can be used reliably in policy analysis. Because 90 percent of all hazardous waste is currently transported by truck (3), the models described in this paper are restricted to truck transport.

RELEASE MODEL DEVELOPMENT

Four general types of risk estimation methodologies have thus far evolved and been applied to the various aspects of transport risk analysis. [For an overview of this topic, see TRB Special Report 197 (4) and NCHRP Report 103 (5).] These methodologies are statistical inference, fault-tree modeling, simulation modeling, and subjective estimation. Each of these techniques has advantages and disadvantages, which must be evaluated in any given case. For example, the primary limitation of statistical estimation techniques is that one must assume the process generating the accident or incident frequencies to be stationary. Otherwise the estimates obtained from past data could not be used to predict future occurrences. Unlike statistical estimation methods, fault-tree analysis attempts to model the incident occurrence process in great detail. Although this has scientific appeal, there are difficulties associated with the acquisition of data for predicting basic event probabilities and the uncertainty that all significant event sequences have been considered. Nevertheless, fault-tree analysis as applied to the estimation of the risk of transporting hazardous materials has been used in several studies, among which are those by Rhoads (6), Bercha (7), and Geffen (8). Other studies relevant to the evaluation of risk in hazardous material transport include those by Gaylor (9), Jones et al. (10), and the National Transportation Safety Board (NTSB) (11). The reader is referred to a comprehensive bibliography on this subject provided by Russell et al. (12). Of the various techniques discussed in the literature, statistical estimation was considered to be the most appropriate for this study in terms of the overall project objectives. The results of other researchers were used to check the credibility of the estimates.

Incidents involving release of hazardous waste during transport result from any of a number of causes (failure modes) and can occur at shipment terminal points or en route. Of those that occur en route, a certain proportion result directly from truck accidents. Thus, three types of incidents are defined:

1. Container failures due to vehicular accidents en route,
2. Container failures occurring en route due to causes other than vehicular accidents, and
3. Failures at the shipment terminal points.

In developing the transport release model, certain postulates were made concerning the three types of incidents defined earlier:

1. The probability of a truck accident in which a release occurs is independent of the waste being shipped and the container type used in shipment.
2. The probability of occurrence of an incident at any point along the route is a nonzero constant that, exclusive of the truck accidents, depends on the container type used.
3. The probability of occurrence of an incident at a shipment terminal point depends only on the container type used.
4. The expected amount released as a result of an incident depends on the container type used and the specific cause of the release (failure mode). It does not depend on the location of the incident.

The transport release model is formulated as follows:

$$\begin{aligned} R_{tr} = {} & \underline{R} \times \underline{\Lambda} \times d \text{ (expected fraction released en route)} \\ & \underline{R} \times \underline{\theta} \text{ (expected fraction released at terminal point)} \end{aligned}$$

where

R_{tr} = expected released fraction,
$\underline{R}$ = vector of parameters corresponding to the expected fraction released for each defined failure mode,
$\underline{\Lambda}$ = probability vector corresponding to incidents en route for each defined failure mode,
$\underline{\theta}$ = probability vector corresponding to incidents at terminal points for each defined failure mode, and
d = distance shipped.

For each container type considered, it is necessary to estimate the vectors $\underline{R}$, $\underline{\Lambda}$, and $\underline{\theta}$. Thus, the total number of parameters to be estimated depends on the number of container types and failure modes defined. The primary source of data for estimating the incident probability and fraction released vectors was the 1981 Hazardous Material Incident File (HAZMAT) maintained by the U.S. Department of Transportation's Materials Transportation Bureau (MTB). The HAZMAT file is a compilation of nationwide data regarding incidents involving hazardous material spills. As such, it contains information relating to frequency and circumstances (container involvement, failure mode, etc.) surrounding these incidents. This file allows the coding of up to 334 container types and 23 failure modes. Analysis of the data resulted in the identification of the following eight container classes with reasonably uniform physical characteristics and incident involvement rates:

1. Cylinders,
2. Cans,
3. Glass,
4. Plastic,
5. Fiber boxes,
6. Tanks,
7. Metal drums, and
8. Open metal containers.

For each of these eight container classes, expected release estimates were derived, as described in the following sections.

INCIDENT OCCURRENCE MODEL

Given the previous assumptions that the probability of an incident is constant along all points on a given route, it follows that the probability of occurrence of an incident somewhere along the route is directly proportional to the length of the route. Thus, for the first two incident types (incidents en route), the total transport distance is the exposure. For incidents at shipment terminal points, the number of shipments is the exposure because distance is not a factor. Given the foregoing conditions for each container class and failure mode, it can be shown that the limiting probability distributions for each of the incident types and failure modes are given as follows:

Container Failure During Vehicular Accident:

$$P\{n_1 | S, \lambda, \mu_d\} = \exp(-\lambda \mu_d S)(\lambda \mu_d S)^{n_1}/n_1! \qquad (1)$$

Container Failure En Route:

$$P\{n_j | S, \lambda_j, \mu_d\} = \exp(-\lambda_j \mu_d S)(\lambda_j \mu_d S)^{n_j}/n_j! \quad j = 2, 23 \qquad (2)$$

Container Failure at Terminal Point:

$$P\{m_j | S, \theta_j\} = \exp(-\theta_j S)(\theta_j S)^{m_j}/m_j! \quad j = 1, 23 \qquad (3)$$

where

S = number of shipments,
μ_d = mean shipment distance, and
λ and θ = corresponding incident rates for the particular container class.

Direct estimation of the incident rates (λ_j and θ_j) requires knowledge of the number of shipments (S) and the mean shipping distance (μ_d) for each container class. Because the former is not available and cannot be reasonably estimated, the incident-rate estimators (excluding vehicular accidents) were derived in terms of a releasing truck accident rate, which is to be independently assessed. The releasing truck accident rate is some fraction of the overall truck accident rate, accounting for the fact that not all truck accidents result in a material spill. Thus,

$$\tilde{\lambda}_j = [(n_j + 1)/n_1]\hat{\lambda} \quad j = 2, 23 \qquad (4)$$

$$\tilde{\theta}_j = [(m_j + 1)/n_1]\hat{\lambda}\tilde{d} \quad \text{for all } j \qquad (5)$$

where

$\hat{\lambda}$ = estimate of the accident rate for trucks in which releases occur [$\hat{\lambda} = 2.8 \times 10^{-7}$ (13)];
$\tilde{d}$ = estimate of μ_d, determined from the HAZMAT data; and
n_j and m_j = incident frequencies for the container class obtained from the HAZMAT file.

FRACTION-RELEASED MODEL

The fraction-released model is made up of two submodels: one for the fraction of containers failed given an incident and the other for the fraction spilled given failure. These are henceforth referred to as the failure and spill models, respectively. Given the assumed dependence of the fraction-failed and fraction-spilled variables on both the container type and failure mode, linear models are constructed as follows:

$$F = \alpha_0 + \alpha_1 X_1 \ldots + \alpha_7 X_7 + \beta_1 Y_1 + \ldots + \beta_{22} Y_{22}$$

$$P = \gamma_0 + \gamma_1 X_1 \ldots + \gamma_7 X_7 + \delta_1 Y_1 + \ldots + \delta_{22} Y_{22} \qquad (6)$$

where F and P denote the fraction failed and fraction spilled and the X's and Y's are binary variables denoting the container classes and failure modes, respectively. For example, an observation corresponding to container class 1 and failure mode 6 would have $X_1 = 1$ and $Y_6 = 1$ and the remaining independent variables would be zero.

The full regression models contain 29 binary variables (needed to define the 8 container classes and 23 failure modes), with the assumption that the interaction terms are not significant. The regression coefficients in the models were estimated by using the spill data in the HAZMAT file.

Let F_j, P_j, and R_j denote the random variables fraction failed, fraction spilled, and fraction released for failure mode j; the means are μ_{fj}, μ_{pj}, and μ_{rj}, respectively. Thus, $R_j = F_j P_j$. Assuming that F_j and P_j are independent, $\mu_{rj} = \mu_{fj}\mu_{pj}$. Denoting by r_j the estimate of μ_{rj}, one obtains

$$r_j = f_j p_j \qquad (7)$$

where f_j and p_j are the mean response estimates obtained from the models of Equation 6.

Recall that λ_j and θ_j denote the probabilities of incident occurrences by failure mode j en route and at the terminal points, and $\tilde{\lambda}_j$ and $\tilde{\theta}_j$ are their estimators. Let μ_r and μ_{rt} denote the mean fraction released per mile shipped and at terminal points, respectively. Let r and r_t denote the respective estimators. Then

$$r = \sum_{j=2}^{23} r_j \tilde{\lambda}_j + r_1 \lambda' \qquad (8)$$

$$r_t = \sum_j r_j \tilde{\theta}_j \qquad (9)$$

where λ', corresponding to the failure mode of a releasing vehicular accident, is considered an input variable. Several values for λ' will be given below for different highway types, of which the composite rate ($\hat{\lambda}$) was used in the estimation of the incident probabilities ($\tilde{\lambda}_j$ and $\tilde{\theta}_j$).

PARAMETER ESTIMATION

In the previous section, estimators of the expected fraction released were derived based on the failure and spill models. Table 1 gives the computed estimates for each of the container classes both for incidents en route and at terminal points.

TABLE 1 Estimates of Fraction Released by Container Class

Container Class	Expected Fraction Released per Mile Shipped	Expected Fraction Released at Terminal Points
1	$1.3 \times 10^{-6} + (0.13\lambda')$	1.4×10^{-4}
2	$2.6 \times 10^{-6} + (0.12\lambda')$	4.0×10^{-4}
3	$1.7 \times 10^{-6} + (0.27\lambda')$	2.6×10^{-4}
4	$4.1 \times 10^{-6} + (0.14\lambda')$	5.2×10^{-4}
5	$1.3 \times 10^{-6} + (0.12\lambda')$	6.1×10^{-5}
6	$4.2 \times 10^{-8} + (0.19\lambda')$	7.6×10^{-6}
7	$2.4 \times 10^{-6} + (0.10\lambda')$	2.9×10^{-4}
8[a]	7.5×10^{-6}	1.2×10^{-3}

[a] Estimate associated with the released fraction during accident is not reliable.

Note in the table that the expected fraction released per mile shipped has been expressed in terms of λ', a rate for truck accidents in which a release occurs. From an independent analysis of data on truck accident rates (13) and the work of Vallette et al. (14) and of others (15-23), the following estimates of accident rates (releasing accidents per million truck miles) for three different highway types have been derived:

Highway Type	Accident Rate
Interstate	0.13
U.S. and state (rural)	0.45
Interrupted flow due to intersections (urban)	0.70
Composite	0.28

In computing the foregoing estimates, it is necessary to take into account that not all truck accidents result in a release. An estimate of 0.2 for the fraction of truck accidents in which a spill occurs was derived. This was based on the following factors. First, the 1982 FRA Accident/Incident Bulletin (24) indicates that in 601 train accidents consisting of 2,770 cars carrying hazardous materials, 109 cars released. Second, previous work by Geffen (8) indicates that tank trucks involved in accidents are approximately 10 times more likely to spill than rail tank cars. These two factors yield an estimate of 0.4, which was adjusted downward to compensate for the higher damage threshold for an FRA reportable accident than the threshold used in the HAZMAT file. It is emphasized that the releasing accident rates reported here are suggested values that in a given situation should be replaced by more accurate estimates if they are available.

In order to evaluate the results, estimates for tanks in Table 1 were compared with the results of the Bercha study (7) for tank trucks and vacuum trucks and the Pacific Northwest Laboratory (PNL) studies (6,8) for tank and tank-trailer combination trucks. The PNL studies report incident probabilities in a 130-mile (210-km) shipment of 3.68×10^{-5} and 3.57×10^{-5} for propane- and gasoline-carrying trucks, respectively. These values translate to an incident probability per mile of 2.8×10^{-7}, which compares favorably with the current estimate for the fraction released per mile of 1×10^{-7}. The Bercha study reports fractions released per mile of 2.02×10^{-7} and 1.68×10^{-7} for vacuum trucks and tank trucks, respectively. In addition, Bercha reports estimates of the fraction released during loading and unloading of 4.6×10^{-4} and 2.4×10^{-4} for vacuum trucks and tank trucks, respectively. The current results for incidents en route are in general agreement with those of Bercha. For incidents at terminal points, however, they are two orders of magnitude lower. This apparent discrepancy could result from underreporting of HAZMAT small spill incidents at terminals. After the small spills have been removed from the Bercha analysis, the resulting fractions released during loading and unloading for both vacuum and tank trucks become 2.4×10^{-5}. These are still three times higher than this study's estimate of 7.6×10^{-6}.

ERRORS OF THE ESTIMATES

There are several sources of error that affect the release estimates in Table 1. These can be categorized as modeling errors and estimation errors. In this section, only the estimation errors and their implications are discussed.

Recall that in Equations 4 and 5, there are three factors to be estimated: λ, the accident rate for trucks in which releases occur; μ_d, the mean shipping distance for the container class; and the incident frequency ratios. In view of the functional form of the estimators, the errors in the aforementioned factors are multiplicative. That is, a 10 percent error in $\hat{\lambda}$ and a 10 percent error in $(n_j + 1)/n_1$ yields a 21 percent error in $\tilde{\lambda}_j$. The error in $\hat{\lambda}$, in turn, is multiplicative in the errors in the accident rate estimates and the estimates of the fraction of accidents that release. In order to gauge the total error, each of the factors is considered separately.

The frequency ratios derived from the HAZMAT data could be affected by underreporting of incidents. There is strong evidence to suggest that this occurs. However, if the underreporting is uniform across all failure modes, the estimates are not affected. It is the authors' view that accidents are not as likely to go unreported as are other incidents (particularly at terminals) and this would lower the estimates.

The estimates of the truck accident rates derived in this study are within the range of previously reported findings. As an average of rates representing varied highway and traffic volume conditions, the composite rate used in the analysis is lower than what was used in the PNL (6,8) and Bercha (7) studies. This again would tend to lower the estimates.

With regard to the estimate of the fraction of accidents that release, it may be argued that the estimate of 0.2 is high. For example, it has been suggested that one can use the fatality rate as a proxy for the releasing accident rate. From data reported by NHTSA (23), 8.6 percent of single-vehicle truck accidents result in a fatality. NHTSA also reports injury rates of 24 percent. Thus, a factor in the range of 0.08 to 0.24 appears reasonable.

There are other factors the errors of which affect the computations of the final estimates of the fraction released. These include sampling errors in the estimates of the fraction spilled given an accident and errors in the estimation of the shipping distances by container types. The magnitude of these errors is given by the standard error of the estimates and is less than 20 percent.

As an illustration of the overall error effects, consider the possibility that the accident rate was underestimated by 25 percent, the fraction of releasing accidents was overestimated by 100 percent, the shipping distance was overestimated by 20 percent, and the frequency ratio at terminals was underestimated by 20 percent. For the foregoing situation, the net error in the incident probability estimates would be approximately 44 percent.

ESTIMATING THE EXPECTED AMOUNT RELEASED

From the model parameters described previously, the following procedure is used to estimate the expected fraction released during transport in a given application:

1. Identify shipment characteristics (e.g., number of shipments, volume per shipment, trip distance, and container type),
2. Identify roadway characteristics (highway type),
3. Select appropriate values of the parameters for the fraction released for the container type being considered,
4. Select appropriate λ',
5. Determine fraction released en route and at terminal points,
6. Multiply fraction released en route by total trip miles and fraction released at terminal points by the number of shipments,
7. Add these values to arrive at total expected fraction released, and
8. Multiply this by the total volume to obtain the total expected amount released.

To illustrate this procedure, consider the problem of estimating the expected amount released given that two hundred 55-gal drums are being shipped a distance of 100 miles on Interstate highways.

The accident rate for Interstates has been given as $\lambda' = 0.13$ releasing accident per million truck miles. The expected amount released en route and at the terminal points is obtained by using the information from Table 1 as follows:

E (release en route) = $(2.4 \times 10^{-6} + 0.10 \times 0.13 \times 10^{-6}) \times 100 \times 200 \times 55 = 2.6$ gal.

E (release at terminals) = $2.9 \times 10^{-4} \times 200 \times 55 = 3.2$ gal.

Total expected release = 5.8 gal = 0.05 percent of total shipment.

ESTIMATION OF TRANSPORT COST

Literature Review

During the literature review process, seven studies were identified as having treated the issue of estimating the cost of transporting hazardous waste by truck. (Several other cost studies of truck transport exist that do not explicitly focus on hazardous waste transport.) In all cases, this issue was considered within the larger scope of addressing the total cost and risk of hazardous waste treatment at a regional level. The subsequent discussion describes the methodology adopted in each study.

In a report to the Environmental Council of Alberta concerning the risks of transportation of hazardous waste substances, Bercha (7) addressed the cost of hazardous waste transportation by segmenting according to trip length (1 km = 0.6 mile):

	Cost	
Trip Length (km)	Canada ($/tonne-km)	United States ($/ton-mile)
0-100	0.120	0.176
>100	0.080	0.117

Bercha did not differentiate by truck capacity and material carried. Although not reported, it is assumed that trip length corresponds to one-way trip distance and that the costs of deadheading back to the trip origin are embedded in this cost structure. It is also assumed that the trip length segmentation was established to reflect the decrease in costs per ton mile that will occur with longer trips as fixed costs are distributed over a larger base.

A study by Booz-Allen and Hamilton (25) addressed transport costs as part of an assessment of hazardous waste generation and treatment capacity. Booz-Allen assumed that all hazardous waste would be transported by either 6,000-gal tank trucks or flatbed trucks carrying 80 drums. It was implied that trucks would be traveling at full capacity. On the basis of interviews with facility operators, three different rules of thumb were established:

Method	Cost ($)
Flat rate per hour	30.00-40.00
Flat rate per mile, round trip	1.50-3.00
Fixed cost plus variable cost (usually applied to shorter trips)	100.00-150.00 minimum charge and 1.00-1.50 per mile

The Booz-Allen study did not indicate the conditions under which each costing method is most appropriate. The study also assumed that the costs are similar for transporting waste by tank or drum, and it did not recognize the expected decrease in per-mile costs associated with longer trips. Finally, the assumption that trucks travel at full capacity is not supported by analyses that have been conducted on hazardous waste shipment characteristics (13). As a result, the estimated costs are likely to be biased toward underreporting the actual cost of transport.

In their study of the New York State hazardous waste management program, Camp et al. conducted telephone interviews with haulers operating within the state (26). Cost estimates were solicited for a 75-mile one-way trip by using 4,000-gal tank trucks. The cost estimates (including all fees, tolls, gas, and wages) ranged from $1.14 to $4.80 per trailer mile depending on distance, waste type, and quantity. For their purposes, Camp et al. used an average cost of $1.25 to $1.50 per mile.

The importance of this study is not what Camp et al. adopted for their use (which suffers from the deficiencies described previously in the discussion of the Bercha and Booz-Allen studies), but in the information obtained in conversing directly with operators. The operators themselves identified trip distance, shipment size, and waste type as being important factors in determining transport cost.

Transport cost was treated quite generally in a study of hazardous waste management in Massachusetts

(27). It was assumed that waste would be transported in either 80-drum trucks or 4,400-gal tanker trucks, and it was further assumed that trucks only travel at capacity. Costs were estimated at \$1.00 to \$3.00 per truck mile (one-directional travel), which is equivalent to \$0.06 to \$0.18 per ton mile. The Massachusetts study adopted a rate of \$0.12 per ton mile for their purposes. No additional insights can be gained from reviewing this costing approach. Beyond assuming that shipments are only made at full capacity, the methodology suffers from assuming that per-mile costs remain constant irrespective of trip length and material carried.

In contrast to the variable cost structure established in the previously described studies, Arthur D. Little, Inc. (ADL), developed a more sophisticated approach in their assessment of hazardous waste management facilities in New England (28). In this study it was recognized that the real cost of transporting waste consists of a fixed cost (capital amortization, insurance, taxes, salaries, fringe benefits, supervision, and general and administrative costs) independent of the shipment activity and a variable cost (fuel, tires, lubrication, maintenance), which is likely to be a function of trip distance.

To arrive at their cost formulas, ADL assumed that a truck is in service 2,000 hr per year and during the time that the truck is in service and on the road, the average travel speed is 40 mph. It was further assumed that the truck operates at capacity when a shipment is made and returns empty to the trip origin. Tank trucks and stake trucks with 6,000-gal capacity that can carry thirty 55-gal drums were examined.

With this information, cost functions were derived of the following form:

$$\text{Tanker } C_T = (0.084 + 2.45)/d \qquad (10)$$

$$\text{Stake truck } C_T = (0.237 + 11.01)/d \qquad (11)$$

where C_T is the cost in dollars per ton mile and d is the one-way trip distance in miles.

The major advantage of the ADL approach is the detail given to components that are part of the cost of providing transport service and the recognition that some costs are fixed whereas others are variable in nature. This methodology accounts for different truck types and unit costs that decrease as a function of trip distance. The drawbacks of this work are as follows:

1. The estimates of capital and operating costs were not validated against actual records,
2. It was assumed that trucks were at full capacity during transport, and
3. It was assumed that trucks were constantly in demand and available for service.

These assumptions contribute a bias toward underestimating the real transport cost per shipment.

A revised costing procedure was developed by ADL for their study of hazardous waste quantities and facility needs in Maryland (29). The primary modifications to their earlier methodology were

1. The assumption that trucks were in service 80 percent of the time,
2. Inclusion of a line item for profit (5 percent of non-capital-related expenses plus general and administrative expenses),
3. Consideration of a roll-off container truck with capacity for eighty 55-gal drums, and
4. An update to the component costs to account for inflation and other changing market conditions.

For the Maryland study, ADL did contact several operators in the United States to verify the plausibility of the cost assumptions.

Estimates of the cost per ton for one-way trip distances of 50 and 100 miles for tank trailers and roll-off containers (using a stake truck) were made. ADL also developed generalized cost formulas in their study.

This approach resolves many of the criticisms raised in the review of previous methodologies. The major remaining problems are the assumption of fully loaded trucks and, although operators were consulted on the component cost estimates, the failure to examine actual cost records for the purposes of establishing the representativeness of the entire costing procedure.

For the EPA RCRA Risk/Cost Analysis Model, ICF, Inc., examined the costs of transporting waste by 6,000-gal tank trucks for one-way trip distances of 25 and 250 miles (30). It was assumed that on-site transportation costs were included in treatment and disposal costs, which appears to be an implied assumption in the other studies that have been reviewed.

ICF's approach was to formulate a procedure similar to that developed by ADL. Notable differences in the two approaches are the absence in the ICF formulation of the following: supervisory labor, interest on capital, insurance, tax, general and administrative costs, and profit. The ICF procedure suffers from the same deficiencies as the ADL Maryland methodology and, in addition, is not as comprehensive. For these reasons, the ICF approach appears less suitable.

In summary, the methodologies reviewed fall into two major categories: variable-cost models and total-cost (fixed plus variable) models. The total-cost models are more sophisticated in their treatment of component costs and are likely to be more representative of the real cost of operating service. Of the total-cost models, the ADL Maryland approach appears to be the most complete, although some deficiencies still remain. In the following section a revised procedure is described that was developed to address these deficiencies.

Revised Procedure

The revised costing procedure was developed based on ADL cost assumptions with the following modifications:

1. Costs are updated into 1983 terms by using the consumer price index (CPI) where appropriate,
2. Average trip distances and shipment sizes are assumed based on the results of an analysis of hazardous waste shipment characteristics by using manifest data from several states (13), and
3. The revised cost formulas are compared with actual price quotes from waste haulers for purposes of establishing the accuracy of the revised procedure.

Transport costs are estimated for 6,000-gal tankers and 18-ton stake trucks. As in the case of the ADL study, costs are segmented into fixed and variable costs, as described in Table 2.

Average-Cost Approach

Tanker (6,000-gal)

Analysts often require average-cost information in

TABLE 2 Cost Assumptions for Revised Procedure

	Costs ($)	
Type of Cost	Tanker (6,000-gal)	Stake Truck (18-ton)
Fixed		
Capital[a] amortization (8 yr at 12 percent = 0.201)	18,170	16,402
Noncapital fixed (1983[b])		
Driver's salary ($14.64/hr x 2,000)	29,280	29,280
Supervision ($2.93/hr x 2,000)	5,860	5,860
Insurance ($2.10/hr x 2,000)	4,200	4,200
License and tax ($2.00/hr x 2,000)	4,000	4,000
Total capital and noncapital fixed	61,510	59,742
General and administrative at 10 percent	6,151	5,974
Profit at 5 percent	3,383	3,286
Total fixed	71,044	69,002
Variable[c]		
Fuel and oil	0.23	0.23
Tires, maintenance, and repair	0.14	0.14
General and administrative at 10 percent	0.04	0.04
Profit at 5 percent	0.02	0.02
Total variable	0.43	0.43

[a] Capital cost for 6,000-gal tanker = $90,400; for 18-ton stake truck = $81,600.

[b] Using consumer price index (CPI) figures for urban wages, the inflation rate has been as follows: 1981 = 10.4 percent, 1982 = 6.1 percent.

[c] Per mile.

order to make policy decisions when detailed information on shipment characteristics is not available. This can be facilitated by assuming an average shipment size and trip length for a typical shipment. The following analysis examines average costs for tanker transport where it is assumed that the tanker is carrying liquid materials.

The analysis assumes an 80 percent utilization rate (in service 1,600 hr per year), time on the road is based on an average speed of 40 mph, and the loading and unloading time per shipment is 2 hr. Based on the analysis of hazardous waste shipment characteristics, the mean trip length is 84.2 miles and the average shipment size is 3,171 gal, or equivalently, 13.21 tons (13). These inputs, coupled with the information in Table 2, yield the following results:

Average time per shipment = [(84.2 x 2 miles)/40 mph] + 2 hr = 6.21 hr.

Average trips per year = 1,600 hr/6.21 hr = 257.65.

Average fixed cost per trip = $71,044/257.65 = $275.74.

Average variable cost per trip = $0.43 x (84.2 x 2 miles) = $72.41.

Average total cost per trip = $275.74 + 72.41 = $348.15.

Average cost per loaded mile = $348.15/84.2 = $4.14.

Average cost per loaded ton mile = $4.14/13.21 = $0.31.

Thus, the average cost per loaded mile of tanker transport is $4.14 and the average cost per ton mile is $0.31.

Stake Truck (18-ton)

The time, distance, and quantity assumptions remain the same as in the previous case, with the following exceptions:

1. Loading and unloading time is assumed to be 3 hr and
2. Average shipment size is 11.63 tons (13).

The analysis proceeds as follows:

Average time per shipment = [(84.2 x 2 miles)/40 mph] + 3 hr = 7.21 hr.

Average trips per year = 1,600 hr/7.21 hr = 221.9.

Average fixed cost per trip = $69,002/221.9 = $310.96.

Average variable cost per trip = $0.43 x (84.2 x 2 miles) = $72.41.

Average total cost per trip = $310.96 + $72.41 = $383.37.

Average cost per loaded mile = $383.37/84.2 = $4.55.

Average cost per loaded ton mile = $4.55/11.63 = $0.39.

The average costs per loaded mile and loaded ton mile are larger for stake trucks than for tankers. This is because of the smaller loads associated with stake trucks.

Deriving Cost Formulas

It is extremely useful to have formulas available to estimate the cost of transport when details on specific shipments are available. These formulas are derived for tankers and stake trucks in the following discussion. The average cost per loaded mile (clm) in dollars per loaded mile can be expressed as follows:

$$\mathrm{clm} = \{F/[1{,}600/(0.05X + Z)]\}(1/2X) + (0.43 \times 2) \tag{12}$$

where

F = annual fixed cost,
X = one-way shipment length (miles),
Y = shipment size (tons), and
Z = loading and unloading time (hr).

For tankers, $F = \$71{,}044$ and $Z = 2$. Therefore,

$$\mathrm{clm}_{\mathrm{tanker}} = 3.08 + (88.8/X).$$

The cost per loaded ton mile (ctm) in dollars per loaded ton mile for tankers is

$$\mathrm{cltm}_{\mathrm{tanker}} = (3.08/Y) + (88.8/XY).$$

For stake trucks, $F = \$69{,}002$ and $Z = 3$. Therefore,

$$\mathrm{clm}_{\mathrm{stake}} = 3.02 + (129.38/X).$$

The cost per loaded ton mile for stake trucks is

$$\mathrm{cltm}_{\mathrm{stake}} = (3.02/Y) + (129.38/XY).$$

Comparison with Actual Charges

The cost estimates using the revised costing procedure were compared with actual rates charged by haulers to determine the accuracy of the costing procedure. Information on actual rates was obtained from a study of transportation costs of hazardous waste haulers conducted by Temple, Barker and Sloane, Inc., (TBS) in May 1983 (31).

In their study, TBS contacted 10 companies involved in the treatment, disposal, and transportation of hazardous waste to gather cost information on drum and bulk waste transport activities. TBS experienced considerable difficulty in obtaining cost information that could be used to directly compare one operation with another. In fact, companies varied in terms of type of truck, vehicle capacity, area of service, average haul distance, quoted rates, and units to establish rates. Nevertheless, TBS attempted to establish a uniform scale by converting all rates to dollars per loaded mile.

For 5,000- to 6,000-gal tankers, quoted rates ranged from $2.75 to $4.50, with an average of $3.40. The average cost per loaded mile using the revised costing procedure is $4.14, which is toward the upper bound of what most shippers are charging. However, the lower costs in the range were quoted for one-way trips of 200 to 300 miles, well above the average trip distance used to compute the average cost per mile in the costing procedure. Using the cost formula for tankers with a one-way trip distance of 300 miles, the estimated average cost is $3.38 per loaded mile, which is consistent with the amount operators are reportedly charging for a 300-mile one-way trip.

For stake trucks capable of handling 70 to 88 drums, the rate per loaded mile ranged from $2.10 to $4.00, with an average of $3.30 as compared with the estimated average of $4.55. Again, the lower rates were associated with longer trips. Using the cost formula for stake trucks, the estimated cost per loaded mile for a 300-mile one-way shipment is $3.45, which compares rather favorably with reported rates.

In conclusion, the cost formulas appear to be representative of quoted rates in the hazardous waste transport industry, particularly for the long-haul market. The average-cost figures, however, should be treated more carefully and should only be employed when information is not available on shipment size and trip distance.

SUMMARY

In this paper the results of a study are reported in which expected release rates are derived for the truck transport of hazardous materials and wastes. The results indicate that in terms of order of magnitude, the expected fractions released per mile shipped range from 10^{-8} to 10^{-6}, depending on the container used in transport. Expected release fractions at terminal points ranged from 10^{-6} to 10^{-3}, also depending on the container class.

The computed estimates indicate that

1. The release rates for tanker trucks are much lower than those for other container types,
2. The expected amount released at terminal points is one to three orders of magnitude higher than the amount released en route (depending on trip length), and
3. The release rates during transport are potentially as high as the corresponding rates at disposal sites and treatment facilities, which range from 10^{-7} to 10^{-3} for routine spillage and 10^{-5} to 10^{-3} for accidental spillage (2).

The implication of the reported findings for policy analysis is that the transportation-related aspects of the hazardous waste disposal problem deserve considerable attention.

In this paper methods for estimating the cost of transporting hazardous waste by truck were also reviewed. Previous work has varied from gross estimates of the unit cost of transport to more sophisticated derivations of cost based on fixed and variable components. Several deficiencies were noted in previous work, particularly assumptions related to shipment characteristics and a lack of comparison with actual rates charged by waste haulers.

A revised procedure was developed with the objective of overcoming these deficiencies. Based on this approach, new cost formulas were derived for estimating the cost of waste transport by tanker and stake truck. Cost estimates based on these formulas compared quite favorably with industry quotes. Consequently, it is believed that these formulas can be adopted for use in policy analysis.

Taken together, the release and cost models described in this paper can be used to address several levels of policy analysis involving hazardous waste management. This includes the development of optimal truck routing based on minimizing risk and cost over the network or identifying the optimal location of hazardous waste disposal and treatment facilities based on transport, treatment, and disposal considerations.

ACKNOWLEDGMENT

This work was supported by the Office of Solid Waste of the U.S. Environmental Protection Agency. The authors are grateful for the advice and cooperation of Curtis Haymore, Arline Sheehan, Eric Males, and Jean Tilly of the EPA Office of Solid Waste. The assistance provided by Joseph Kirk, Leslie Kostrich, and Stephen Bailey of ICF, Inc., is also appreciated. Finally, Russell Capelle of ATA, Inc., offered several useful comments during the review process that positively affected the final results. Special thanks are extended to Betty Alix for preparation of this document.

REFERENCES

1. National Survey of Hazardous Waste Generators and Treatment Storage and Disposal Facilities Regulated Under RCRA in 1981. Draft Final Report. Westat Research, Rockville, Md., Jan. 1984.
2. The RCRA Risk/Cost Analysis Model: Phase 3 Report. ICF, Inc.; Office of Solid Waste, U.S. Environmental Protection Agency, Jan. 1984.
3. Characterizations of Hazardous Waste Transportation and Economic Impact Assessment of Hazardous Waste Transportation Regulations. U.S. Environmental Protection Agency, March 1979.
4. Transportation of Hazardous Materials: Toward a National Strategy. Special Report 197. TRB, National Research Council, Washington, D.C., 1983.
5. Risk Assessment Processes for Hazardous Materials Transportation. NCHRP Report 103. TRB, National Research Council, Washington, D.C., 1983.
6. R.E. Rhoads. An Assessment of the Risk of Transporting Gasoline by Truck. Report PNL-2133. Pacific Northwest Laboratory, U.S. Department of Energy, Richland, Wash., Nov. 1978.
7. F.G. Bercha et al. Risks Associated with the Transportation to Treatment of Hazardous Waste Substances: Phase 1. Environmental Council of Alberta, Edmonton, Alberta, Canada, Dec. 1980.
8. C.A. Geffen. An Assessment of the Risk of Transporting Propane by Truck and Train. Report PNL-3308. Pacific Northwest Laboratory, U.S.

Department of Energy, Richland, Wash., March 1980.
9. D.W. Gaylor. Statistical Methods in Risk Assessment. Presented at Water Pollution Control Federation, Anaheim, Calif., 1978.
10. G.P. Jones, R.W. Barrow, L.C. Stuckenbruck, E.L. Holt, and R.P. Keller. Risk Analysis in Hazardous Material Transportation, Vol. 1. Final Report TES-20-73-4-1. U.S. Department of Transportation, March 1973.
11. Risk Concepts in Dangerous Goods Transportation Regulations. Report NTSB-STS-71-1. National Transportation Safety Board, Jan. 1971.
12. E.R. Russell, J.J. Smaltz, J.D. Lambert, V.P. Delines, R.L. Jepsen, P.G. Joshi, and T.R. Mansfield. Risk Assessment User's Manual for Small Community and Rural Areas. Report DOT/RSPA/DPB-50/81/30. Railway Systems and Procedures Association, U.S. Department of Transportation, Oct. 1981.
13. M.D. Abkowitz, A. Eiger, and S. Srinivasan. Assessing the Releases and Costs Associated with Truck Transport of Hazardous Wastes. Office of Solid Waste, U.S. Environmental Protection Agency, Jan. 1984.
14. G.R. Vallette, H.W. McGee, J.H. Sanders, and D.J. Enger. The Effect of Truck Size and Weight on Accident Experience and Traffic Operations, Vol. 3: Accident Experience of Large Trucks. Report FHWA/RD-80-137. FHWA, U.S. Department of Transportation, July 1981.
15. The Safety of High Gross Weight Trucks. Arthur D. Little, Inc., Cambridge, Mass., March 1974.
16. Review of Safety and Economic Aspects of Increased Vehicle Sizes and Weights. FHWA, U.S. Department of Transportation, Sept. 1969.
17. Safety Comparison of Doubles Versus Tractor-Semitrailer Operation. Bureau of Motor Carrier Safety, FHWA, U.S. Department of Transportation, Nov. 1977.
18. R. Zeiszler. A Study of California Truck Accidents. California Highway Patrol, Sacramento, April 1973.
19. R.E. Scott and J. O'Day. Statistical Analysis of Truck Accident Involvements. Report DOT-HS-800-627. NHTSA, Dec. 1971.
20. C.S. Yoo, M.L. Reiss, and H.W. McGee. Comparison of California Accident Rates for Single and Double Tractor-Trailer Combination Trucks. Report FHWA-RD-78-94. FHWA, U.S. Department of Transportation, March 1978.
21. R.N. Smith and E.L. Wilmot. Truck Accident and Fatality Rates Calculated from California Highway Accident Statistics for 1980 and 1981. Nov. 1982.
22. W.S. Meyers. Comparison of Truck and Passenger-Car Accident Rates on Limited-Access Facilities. In Transportation Research Record 808, TRB, National Research Council, Washington, D.C., 1981, pp. 48-55.
23. Large Truck Accident Causation. Report DOT-HS-806-300. NHTSA, U.S. Department of Transportation, July 1982.
24. Accident/Incident Bulletin 150. Federal Railroad Administration, U.S. Department of Transportation, June 1982.
25. Hazardous Waste Generation and Commercial Hazardous Waste Management Capacity: An Assessment. Booz-Allen and Hamilton, Inc.; Office of Planning and Evaluation and Office of Solid Waste, U.S. Environmental Protection Agency, Dec. 1980.
26. Technical, Marketing, and Financial Findings for the New York State Hazardous Waste Management Program. Camp, Dresser and McKee, Boston, Mass., March 1980.
27. Hazardous Waste Management in Massachusetts: Statewide Environmental Impact Report. Massachusetts Bureau of Solid Waste Disposal, Boston, Mass., Aug. 1982.
28. A Plan for Development of Hazardous Waste Management Facilities in the New England Region. Arthur D. Little, Inc., Cambridge, Mass., Sept. 1979.
29. Hazardous Waste Quantities and Facility Needs in Maryland. Arthur D. Little, Inc., Cambridge, Mass., Aug. 1981.
30. RCRA Risk/Cost Policy Model Project: Phase 2 Report. ICF, Inc.; U.S. Environmental Protection Agency, June 1982.
31. Survey of Transportation Costs for Hazardous Wastes. Temple, Barker and Sloane, Inc.; Office of Solid Waste, U.S. Environmental Protection Agency, May 18, 1983.