Truck Accident Rate Model for Hazardous Materials Routing

Douglas W. Harwood, John G. Viner, and Eugene R. Russell

Estimates of accident and release rates are essential for conducting risk assessments in routing studies for highway transportation of hazardous materials. Recently published literature has emphasized both the importance of these rates in risk assessment and the significant shortcomings of the available data. New truck accident rates are developed as a function of roadway type and area type (urban or rural) from state data on highway geometrics, traffic volume, and accidents. Release probabilities in accidents have been derived from a combination of federal and state truck accident data bases. A revised model for the accident probability portion of the U.S. Department of Transportation hazardous materials routing guidelines is recommended, and its application is illustrated using accident and release rates derived to substitute for existing default values. Statistical tests based on the chi-squared and Poisson distributions are provided to determine whether accident rates based on site-specific data or system-wide values, such as those derived here, should be used for any particular route segment.

The most widely accepted risk assessment model for identifying preferred routes for hazardous materials transportation is that presented in the U.S. Department of Transportation (DOT) guidelines. This model was first presented in the 1980 FHWA publication *Guidelines for Applying Criteria to Designate Routes for Transporting Hazardous Materials* (*1*). This document was recently updated and republished by the DOT Research and Special Programs Administration (*2*).

The DOT guidelines are based on the selection of minimum-risk routes, on which risk is determined for individual route segments by the equation

$$\text{Risk} = (\text{Accident Probability}) \times (\text{Accident Consequences}) \quad (1)$$

The DOT guidelines contain procedures for determining (a) accident risk on the basis of accident rate and route segment length, and (b) accident consequences on the basis of either the number of persons potentially exposed or the value of property potentially exposed to hazardous materials releases. Updated procedures and improved data have been developed for assessing the accident probability term in Equation 1.

A recent critique (*3*) has identified several potential approaches to strengthening the accident probability portion of the DOT guidelines. These recommendations are based on several perceived weaknesses in the current guidelines, including the following:

- Default values of accident rates in the DOT guidelines are based on accident predictive models that are 15 to 20 years old and that may be out of date (*4–6*).
- The models apply to accident rates for all vehicle types rather than to truck accident rates. All-vehicle accident rates are based primarily on passenger car accidents, whereas highway transportation of hazardous materials is conducted by truck.
- The DOT guidelines implicitly assume that all accidents are equally likely to result in a hazardous materials release. In fact, recent research (*3,7*) has established that some types of accidents are much more likely than others to result in a release.
- The DOT guidelines recommend that observed accident rates for the specific route segments under analysis, rather than the default values, be used whenever possible. However, no statistical guidance is given on whether the observed accident rate is based on a sufficiently large sample of accidents to be statistically reliable or whether the differences between the observed accident rates and the default values are statistically significant.

Recently, Glickman (*8*) has clearly illustrated the significant quality shortcomings in much of the accident rate data currently available for hazardous materials transportation risk assessments. Better data are needed to substitute for the default values presented in the DOT guidelines. These data can be developed from existing federal and state data bases of truck accident rates and hazardous materials release probabilities. Procedures for applying statistical tests are also needed, in order to determine whether it is better to use observed accident rates from a given highway segment or the truck accident rates derived here.

The truck accident rates presented in following sections are weighted averages of system-wide data for the state highway systems of three states. The selected states have mergeable computer files of accident, roadway, and traffic volume data that were required for this analysis. The quality of data from these three states, which include data on the percentage of trucks in the traffic stream, is among the best in the nation. Accident rates for specific roadway types are known to vary from state to state, so highway agencies that have adequate data are encouraged to develop their own default values of truck accident rates using the procedures outlined. At present, about 15 states are known to have the file-merging capability

D. W. Harwood, Midwest Research Institute, 425 Volker Blvd., Kansas City, Mo. 64110. J. G. Viner, FHWA, 6300 Georgetown Pike, McLean, Va. 22101–2296. E. R. Russell, Department of Civil Engineering, Kansas State University, Manhattan, Kans. 66506.

required to develop system-wide truck accident rates for specific roadway types.

DETERMINATION OF TRUCK ACCIDENT RATES

A key element in comparing the risks of alternative routes for hazardous materials transportation is having reliable data on truck accident rates for use in determining the relative probabilities of hazardous materials releases. The effect of roadway and area type on truck accident rates must be accounted for in routing studies. For example, freeways generally have lower accident rates than other types of highways, and urban highways (especially nonfreeways) generally have higher accident rates than rural highways. These differences between highway and area types are well known for all-vehicle accident rates, but they have only been demonstrated for trucks in studies based on a limited number of highway sections (*3,9,10*). Therefore, in developing improved truck accident rates for use as default values in hazardous materials routing studies, emphasis is placed on accounting for the effects of roadway and area type.

The analysis of truck accident rates required three types of data: highway geometrics, traffic volumes, and accident records. In order for the analysis to be accomplished efficiently, these data had to be available in computerized form using common location identifiers (e.g., mileposts) so that the three types of data could be linked together. Many state highway agencies have been computerizing and linking their data files and have, or soon will have, the capability to perform this type of analysis.

No state currently has the necessary data and linking capability to analyze all public highways in the state. The best systems available include only highways under the jurisdiction of the state highway agency. Preliminary discussions were conducted with several agencies whose mergeable records cover the entire state highway systems, and three state agencies with the most complete, mergeable, and easy-to-use computer files were selected for participation in the study. These states were California, Illinois, and Michigan.

Highway geometric files were needed to define the characteristics of highway segments to which truck volume and accident data could then be added. Highway geometric files typically consist of relatively short route segments (0.35 mi or less in length) for which data on the geometric features of the segment are included. The data extracted from geometric files for each segment were

- Number of lanes,
- Lane structure (divided or undivided),
- Access control (freeway or nonfreeway),
- Direction (one-way or two-way), and
- Area type (urban or rural).

Traffic volume files were used in the analysis to obtain the annual average daily traffic (AADT) and either the average daily truck volume or the percentage of trucks in the traffic stream. In all three states, these truck volume data were given in the same location reference system as the highway geometric and accident data. Because nearly 89 percent of accidents in which hazardous materials are released involve combination trucks (tractor-trailers), it would be desirable to limit the accident analysis to combination trucks only (*3*). Unfortunately, truck volume data for combination trucks are seldom available on a system-wide basis. Therefore, it was necessary to use truck volume data and accident data for all commercial vehicles. Because traffic counts of all commercial vehicles typically include both trucks and buses, it was necessary to include bus accidents in the analysis as well. Although undesirable, the inclusion of data for buses should not have a major effect on the accident rates, because the proportion of bus accidents and bus exposure is usually small (typically less than 5 percent).

The truck accident data used for the analysis were a subset of the accident files for all vehicle types maintained by all state highway agencies. The following accident characteristics were used: the numbers and types of vehicles involved, the type of collision (if any), and the accident severity (most were severe injury). The roadway and traffic characteristics associated with these accidents were obtained from the geometric and traffic volume files. Each accident-involved vehicle was treated as a separate observation (i.e., an accident involving two trucks was counted as two accident involvements).

Data Processing

The processing of these data was conducted in a series of five steps shown in Figure 1, using the Statistical Analysis System.

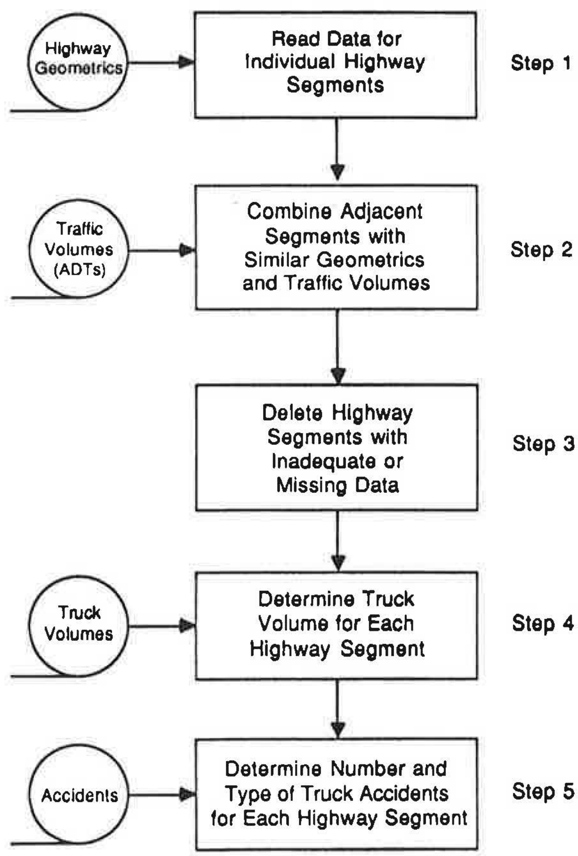

FIGURE 1 Step-by-step process for merging data from highway geometrics, truck volumes, and accident data files.

The key element in the processing was linking the appropriate truck volume and accident data to individual roadway segments from the highway geometric file using common location reference systems (e.g., mileposts). Each step in the linking of the data from these files is described in the following paragraphs.

Step 1

Geometric data needed for the individual roadway segments were read from the highway geometric file. The highway class (roadway type and area type) of each roadway segment was determined from the available data. The highway classes were

- Rural two-lane highways,
- Rural multilane undivided highways,
- Rural multilane divided highways,
- Rural freeways,
- Urban two-lane streets,
- Urban multilane undivided streets,
- Urban multilane divided streets,
- Urban one-way streets, and
- Urban freeways.

Step 2

Individual roadway segments, which have relatively short average lengths, were merged into longer segments whenever adjacent segments matched in highway class and other selected variables and had average daily traffic (ADT) volumes within 20 percent of one another. When adjacent highway segments were merged, their ADT volumes were combined using a weighted average by length, as follows:

$$\text{ADT}_C = \frac{\text{ADT}_1 L_1 + \text{ADT}_2 L_2}{L_1 + L_2} \quad (2)$$

where

ADT_C = average daily traffic volume on combined segments,
ADT_i = average daily traffic on Route Segment i (i = 1, 2), and
L_i = length (mi) of Route Segment i (i = 1, 2).

Step 3

Any roadway segments for which accident or truck volume data were not available or which did not fit within one of the highway classes selected were eliminated from the analysis. The data bases used for this analysis were complete, and only about 0.2 percent of the roadway segments had to be eliminated because of missing data.

Step 4

Truck volumes for the merged sections were obtained from the volume file. The truck volume data were used with the length of the segment to compute the annual vehicle-miles (veh-mi) of truck travel on each segment:

$$\text{TVMT}_i = \text{TADT}_i \times L_i \times 365 \qquad i = 1, 2 \quad (3)$$

where

TVMT_i = annual truck travel (veh-mi) on Route Segment i, and
TADT_i = average daily truck volume in vehicles per day on Route Segment i.

Step 5

Data on truck accidents were obtained from the accident files. Each truck accident involvement was classified by year, accident severity, and accident type. The common location reference system that links the accident and geometric files was used to determine which segment the reported location of each accident fell within and to total the number of accident involvements within each segment by year, severity level, and accident type. The result of Step 5 was a file containing the truck volumes and truck accident histories for individual highway segments that can be used to compute truck accident rates and release probabilities.

Data Analysis

The average truck accident rate for each highway class was computed as the ratio of total truck accidents to total vehicle-miles of truck travel for that highway class. The following equation was used:

$$\text{TAR}_j = \sum_i \frac{A_{ij}}{\text{VMT}_{ij}} \quad (4)$$

where

TAR_j = average truck accident rate for Highway Class j,
A_{ij} = number of accidents in one year on Route Segment i in Highway Class j, and
VMT_{ij} = annual vehicle-miles of travel on Route Segment i in Highway Class j.

This procedure was applied to all existing geometric, traffic volume, and accident files for the state highway systems of California, Illinois, and Michigan that could be linked by mileposts. Tables 1 and 2 present the truck accident rates and truck accident type distributions, respectively, for California. Similar tables were also prepared for Illinois and Michigan state highways. Table 3 presents the average truck accident rates for each highway class in each state and the weighted three-state average.

The truck accident rates in Table 3 are appropriate for use as default values for hazardous materials routing studies in which data more suited to local conditions are not available. Highway agencies are encouraged to develop comparable default values for their own data, whenever possible.

The data in Table 3 clearly indicate the effect of two key variables related to hazardous materials routing—roadway

TABLE 1 TRUCK ACCIDENT RATES ON CALIFORNIA STATE HIGHWAYS, 1985–1987 (*3*)

Highway class: Area type	Highway class: Roadway type	Total length (mi)	No. of sections	Average truck ADT (veh/day)	No. of truck accident involvements[a]	Truck travel (MVM)	Truck[b] accident rate (per MVM)
Rural	Two-lane	8,808.96	2,607	392	6,577	3,784.97	1.73
Rural	Multilane undivided	209.13	334	858	1,070	196.58	5.44
Rural	Multilane divided	726.85	450	1,839	1,801	1,463.45	1.23
Rural	Freeway	2,068.20	405	4,791	5,759	10,850.90	0.53
Rural	TOTAL	11,813.14	3,796	1,260	15,207	16,295.90	0.93
Urban	Two-lane	513.49	648	748	1,778	420.69	4.23
Urban	Multilane undivided	141.50	341	1,116	2,251	172.84	13.02
Urban	Multilane divided	754.18	793	1,644	4,996	1,427.47	3.50
Urban	One-way street	22.26	47	1,387	223	33.81	6.60
Urban	Freeway	1,969.65	817	8,395	28,860	18,107.00	1.59
Urban	TOTAL	3,401.07	2,646	5,414	38,108	20,161.81	1.89
TOTAL		15,214.21	6,442	2,388	53,315	39,781.10	1.34

[a] Accidents involving two or more trucks are counted as two or more involvements.
[b] Computed from Equation (4).

type and area type—on truck accident rate. An attempt was made to determine the relationship between two traffic volume factors (AADT and percentage of trucks) and truck accident rate, but no consistent results were obtained. Consideration of the effects of additional geometric variables (including lane widths, shoulder widths, ramps, intersections, and driveways) on truck accident rates was beyond the scope of the study, but to determine these effects and incorporate them in hazardous materials routing studies as well would be desirable. However, that the development of reliable relationships between geometric features and accidents is a difficult statistical task should be recognized. Previously reported attempts to determine incremental effects of individual geometric features on accident rates have had mixed results, and no set of geometric-accident relationships is widely accepted.

DETERMINATION OF HAZARDOUS MATERIALS RELEASE PROBABILITIES

The probability portion of the DOT routing guidelines is based entirely on accident probabilities. Of course, an accident involving a hazardous materials-carrying truck cannot lead to potentially catastrophic consequences unless the hazardous materials being transported are released. Thus, the current risk assessment methodology implicitly assumes that hazardous materials releases are equally likely in all accidents.

A recent FHWA study (*3,7*) has indicated that the probability of a hazardous materials release given an accident involving a hazardous materials-carrying truck varies markedly with the type of accident. Table 4, created from data from the FHWA motor carrier accident reports, indicates that release probabilities are highest in single-vehicle noncollision accidents and truck-train collisions and lowest in multiple vehicle collisions. Furthermore, the various highway classes have distinctly different patterns of accident types. For example, the percentage of single-vehicle noncollision accidents (which have the highest probability of producing a hazardous materials release if an accident occurs) is about twice as high on rural highways as on urban highways (*3*). Therefore, the probability portion of the DOT guidelines should include a term representing the probability of release given an accident. Default values for this term are developed in Equation 5.

Table 4 was developed from the FHWA motor carrier accident reports because, for each accident-involved truck, this data base documents both whether the truck was carrying hazardous materials and whether the hazardous materials were released. For users to derive values comparable to those in Table 4 for their own state would be desirable, but only three states (Louisiana, Missouri, and Wyoming) currently have both data items needed to make this determination in their accident records systems (*3,7*).

The probability of a hazardous materials release given an accident varies between highway classes because it varies with accident type and because the distribution of accident types varies markedly between highway classes. For example, Table 2 indicates that the proportion of single-vehicle noncollision accidents (which are likely to result in a hazardous materials release) is nearly 50 percent higher on rural two-lane highways than on rural freeways. The probability of a release given an accident involving a hazardous materials-carrying vehicle for a particular highway class can be computed as

$$P(R|A)_j = \sum_k P(R|A)_k \times P(k)_j \qquad (5)$$

where

$P(R|A)_j$ = probability of a hazardous materials release given an accident involving a hazardous materials-carrying vehicle for Highway Class j,

$P(R|A)_k$ = probability of a hazardous materials release given an accident involving a hazardous materials-carrying vehicle for Accident Type k (from Table 4 or equivalent state data), and

TABLE 2 TRUCK ACCIDENT TYPE DISTRIBUTION ON CALIFORNIA STATE HIGHWAYS, 1985–1987 (3)

Highway class		Percent of accident involvements										
		Single-vehicle noncollision accidents			Single-vehicle collision accidents					Multiple-vehicle collision accidents		
Area type	Roadway type	Run-off road	Overturned	Other	Coll. w/ parked vehicle	Coll. w/ train	Coll. w/ nonmotorist[a]	Coll. w/ fixed object	Other collision	Collision w/passenger car	Coll. w/truck	Coll. w/other vehicle
Rural	Two-lane	4.5	6.6	4.4	2.4	0.0	0.6	7.0	5.7	29.8	26.6	12.4
Rural	Multilane undivided	3.6	7.5	3.9	4.3	0.0	0.4	7.5	5.7	27.4	26.1	13.7
Rural	Multilane divided	3.6	4.0	3.8	3.9	0.0	0.2	6.1	4.7	33.4	26.4	13.8
Rural	Freeway	3.5	3.3	3.8	3.8	0.0	0.4	7.4	5.0	31.3	22.3	19.4
Rural	TOTAL	3.9	5.1	4.1	3.2	0.0	0.5	7.1	5.3	30.6	24.9	15.3
Urban	Two-lane	1.5	2.6	3.4	3.6	0.0	0.3	5.1	3.9	39.6	30.7	9.3
Urban	Multilane undivided	0.2	0.6	2.6	8.5	0.0	0.8	5.1	4.0	41.3	30.1	6.9
Urban	Multilane divided	0.8	1.3	2.4	7.0	0.0	0.6	5.7	3.8	43.7	28.1	6.6
Urban	One-way street	0.0	2.2	0.9	9.4	0.0	1.3	6.3	2.2	45.7	27.4	4.5
Urban	Freeway	0.6	1.0	1.3	1.9	0.0	0.2	3.2	1.7	50.6	25.6	13.9
Urban	TOTAL	0.6	1.1	1.6	3.1	0.0	0.3	3.8	2.2	48.6	26.4	12.3
TOTAL		1.6	2.3	2.3	3.1	0.0	0.4	4.7	3.1	43.4	26.0	13.1

[a] Nonmotorists include animals, pedestrians, and bicycles.

TABLE 3 TRUCK ACCIDENT RATES BY STATE AND COMBINED (3)

Highway class		Truck accident rate (accidents per million veh-mi)			
Area type	Roadway type	California	Illinois	Michigan	Weighted average[a]
Rural	Two-lane	1.73	3.13	2.22	2.19
Rural	Multilane undivided	5.44	2.13	9.50	4.49
Rural	Multilane divided	1.23	4.80	5.66	2.15
Rural	Freeway	0.53	0.46	1.18	0.64
Urban	Two-lane	4.23	11.10	10.93	8.66
Urban	Multilane undivided	13.02	17.05	10.37	13.92
Urban	Multilane divided	3.50	14.80	10.60	12.47
Urban	One-way street	6.60	26.36	8.08	9.70
Urban	Freeway	1.59	5.82	2.80	2.18

[a] Weighted by veh-mi of truck travel.

TABLE 4 PROBABILITY OF RELEASE GIVEN THAT AN ACCIDENT HAS OCCURRED, AS A FUNCTION OF ACCIDENT TYPE (3,7)

Accident type	Probability of release
SINGLE-VEHICLE NONCOLLISION ACCIDENTS	
Run-off-road	0.331
Overturned (in road)	0.375
Other noncollision	0.169
SINGLE-VEHICLE COLLISION ACCIDENTS	
Collision with parked vehicle	0.031
Collision with train	0.455
Collision with nonmotorist	0.015
Collision with fixed object	0.012
Other collision	0.059
MULTIPLE-VEHICLE COLLISION ACCIDENTS	
Collision with passenger car	0.035
Collision with truck	0.094
Collision with other vehicle	0.037

$P(k)_j$ = probability that an accident on Highway Class j will be of Accident Type k (i.e., proportion of truck accidents for each accident type presented in Table 2 on Highway Class j from state accident data).

The probabilities in Table 5 are appropriate for use as default values in hazardous materials routing studies if data more suited to local conditions are not available.

REVISED PROCEDURES FOR DETERMINING ACCIDENT PROBABILITIES

In the current DOT guidelines, the probability of a hazardous materials accident is computed in the risk assessment model from the following equation:

$$P(A)_i = \mathrm{AR}_i \times L_i \quad (6)$$

where

$P(A)_i$ = probability of a hazardous materials accident for Route Segment i,
AR_i = accident rate per vehicle-mile for all vehicle types on Route Segment i, and
L_i = length (in miles) for Route Segment i.

The availability of these truck accident rate and release probabilities permits estimation of the probability of a hazardous materials accident in which a release occurs. The probability of a releasing accident should be computed with the following equation (which replaces Equation 6 in the DOT guidelines):

$$P(R)_i = \mathrm{TAR}_i \times P(R|A)_i \times L_i \quad (7)$$

where

$P(R)_i$ = probability of an accident involving a hazardous materials release for Route Segment i,

TABLE 5 PROBABILITY OF HAZARDOUS MATERIALS RELEASE GIVEN THAT AN ACCIDENT HAS OCCURRED, AS A FUNCTION OF HIGHWAY CLASS (3)

Highway class		Probability of hazmat release given an accident			
Area type	Roadway type	California	Illinois	Michigan	Weighted average[a]
Rural	Two-lane	0.100	0.074	0.073	0.086
Rural	Multilane undivided	0.100	0.071	0.064	0.081
Rural	Multilane divided	0.087	0.064	0.062	0.082
Rural	Freeway	0.083	0.111	0.095	0.090
Urban	Two-lane	0.077	0.059	0.069	0.069
Urban	Multilane undivided	0.064	0.052	0.055	0.055
Urban	Multilane divided	0.068	0.048	0.058	0.062
Urban	One-way street	0.066	0.050	0.056	0.056
Urban	Freeway	0.062	0.055	0.067	0.062

[a] Weighted by veh-mi of truck travel.

TAR_i = truck accident rate (accidents per vehicle-mile for Route Segment i,

$P(R|A)_i$ = probability of a hazardous materials release given an accident involving a hazardous materials-carrying truck for Route Segment i, and

L_i = length (mi) of Route Segment i.

Equation 7 is more appropriate for hazardous materials routing analyses than Equation 6 because (a) risk is based on the probability of a hazardous materials release rather than just the probability of an accident, and (b) risk is based on truck accident rates rather than all-vehicle accident rates. Equation 7 retains the proportionality of risk to route segment length, which is central to all routing analyses.

Table 6 presents typical values of truck accident rates and release probabilities taken from Tables 3 and 5 that can be used as default values in Equation 7. However, users are encouraged to develop default values from average data for their own jurisdiction. A key aspect of Table 6 is that both truck accident rates and release probabilities vary with area type (urban or rural) and roadway type.

The DOT guidelines encourage users to base accident rates on site-specific accident histories, whenever possible. The guidelines do not appear to recognize the need for caution in using accident rates based on small sample sizes of accidents, which are typical of the relatively short route segments often used in risk assessments. For example, consider three 0.5-mi route segments on alternative routes. Suppose that, in a 3-year period, one of these segments experiences no truck accidents, another experiences one truck accident, and the third experiences two truck accidents. To treat the first segment as having no risk of a hazardous materials release would certainly be incorrect, but this is the conclusion one would reach using the site-specific accident rate in Equation 6. To presume that, because the third segment has twice as many accidents as the second segment, it also has twice the risk would also be incorrect. The guidelines could be revised to incorporate a minimum time period or a minimum number of accidents needed to establish reliable accident rates. However, because default values of accident rates are available, to rely on default values of accident rates for specific highway classes (e.g., rural two-lane highways or urban freeways) developed on a statewide or system-wide basis is usually more appropriate. An exception to this general rule occurs when the accident frequency for a specific route segment is either substantially higher or lower than the system-wide accident rate for its highway class. Because accident occurrence is a random variable, site-specific accident data cannot be presumed to indicate true

TABLE 6 DEFAULT TRUCK ACCIDENT RATES AND RELEASE PROBABILITY FOR USE IN HAZARDOUS MATERIALS ROUTING AND ANALYSES (3)

Area type	Roadway type	Truck accident rate (accidents per million veh-mi)	Probability of release given an accident	Releasing accident rate (releases per million veh-mi)
Rural	Two-lane	2.19	0.086	0.19
Rural	Multilane undivided	4.49	0.081	0.36
Rural	Multilane divided	2.15	0.082	0.18
Rural	Freeway	0.64	0.090	0.06
Urban	Two-lane	8.66	0.069	0.60
Urban	Multilane undivided	13.92	0.055	0.77
Urban	Multilane divided	12.47	0.062	0.77
Urban	One-way street	9.70	0.056	0.54
Urban	Freeway	2.18	0.062	0.14

differences in risk between segments unless a statistical test indicates that these differences are statistically significant.

In most cases, the truck accident rates shown in Table 6 or, preferably, the average values for the user's own jurisdiction should be used as the value of TAR_i in Equation 7. However, a simple statistical procedure based on the chi-squared test can be used to determine whether the actual accident frequency for a particular route segment is enough larger or smaller than the expected accident frequency to warrant replacement of the default truck accident rates by site-specific rates based on accident histories. This procedure is used as follows.

Step 1

Obtain truck accident data for a particular highway segment. The truck accident data should cover as long a time period as possible without introducing extraneous effects caused by traffic, geometric, or operational changes. This observed accident frequency is referred to as A_o.

Step 2

Compute the expected number of truck accidents for that same time period using system-wide default accident rates such as those presented in Table 6. The expected truck accident frequency can be computed as

$$A_e = \text{TAR} \times \text{TADT} \times L \times 365 \times N \times 10^{-6} \tag{8}$$

where

A_e = expected number of truck accidents,
TAR = expected truck accident rate (accidents per vehicle-mile) on the basis of Table 6 or state data,
TADT = average daily truck traffic (vehicles per day),
L = length of highway segment (miles), and
N = duration of study period (years).

If $A_e \geq 5$, the chi-squared procedure given in Step 3A should be used. If $A_e < 5$, the accident sample size is too small to use the chi-squared procedure, and an alternative procedure (presented in Step 3B) based on the Poisson distribution should be used.

Step 3A

If $A_e \geq 5$, compare the expected and observed number of accidents by computing the chi-squared statistic as follows:

$$\chi^2 = \frac{(A_e - A_o)^2}{A_e} \tag{9}$$

where

χ^2 = chi-squared statistic,
A_e = expected number of truck accidents, and
A_o = observed number of truck accidents.

If $\chi^2 \leq 4$, then the expected and observed number of accidents do not differ significantly at the 5 percent significance level. Therefore, the system-wide default accident rate should be used instead of site-specific accident data.

If $\chi^2 > 4$, then the expected and observed number of accidents differ significantly. This result indicates that the observed accident rate is lower or higher at the 5 percent significance level than the system-wide default value. In this case, the system-wide default accident rate should be replaced by a value based on the site-specific data. If the site-specific accident rate is greater than the default accident rate, the site-specific rate should be used. If the site-specific accident rate is less than 50 percent of the default accident rate, 50 percent of the default accident rate should be used. The latter restriction is based on judgment and is included to keep very low short-term accident experience or poor accident reporting levels in a particular jurisdiction from causing misleading results. Even if the roadway segment has experienced no accidents during the study period, there is still risk involved in transporting hazardous materials over the segment, and use of 50 percent of the default accident rate is recommended.

Step 3B

An alternative procedure based on the Poisson distribution is used whenever $A_e < 5$, because the chi-squared test is not applicable to this small accident sample size. Table 7 presents critical values from the Poisson distribution for testing the significance of differences from the expected number of accidents.

If A_o exceeds the critical value given in Table 7 for the known value of A_e, then the expected and observed accident frequencies differ significantly. In this case, the system-wide default accident rate should be replaced by the site-specific accident rate, calculated as

$$\text{TAR} = \frac{A_o \times 10^6}{\text{TADT} \times L \times 365 \times N} \tag{10}$$

If $A_e < 5$, it is recommended that the default accident rate should never be decreased, because the available sample size is rarely adequate to indicate a true accident rate lower than the expected value.

NUMERICAL EXAMPLES

Two simple numerical examples can illustrate the recommended risk assessment procedures, with emphasis on the revised procedures for determining accident probabilities.

TABLE 7 CRITICAL VALUES OF THE POISSON DISTRIBUTION

Expected accident frequency (A_e)	Critical value of A_o at the 5% significance level
1.0	4
1.5	5
2.0	6
2.5	6
3.0	7
3.5	8
4.0	9
4.5	9

The first example indicates the way a state would use truck accident rates and release probabilities on the basis of its own data. The second example demonstrates use of the default values of truck accident rates and release probabilities in Table 6.

Both examples address the relative risks of hazardous shipments on the simple highway network shown in Figure 2. Hazardous materials shipments must move from Point 1 to Point 5 by either Route A or Route B, which are 16.5 and 11 mi long, respectively. Route A is composed of three segments designated 1–2, 2–3, and 3–5, and Route B is composed of two segments designated 1 4 and 4 5. Route A has a substantial proportion of its length on nonaccess-controlled facilities (two-lane and multilane divided highways), whereas Route B is entirely on freeways. Route B is shorter than Route A, but nearly half of its length is in an urban area with a high population density. Route A is longer but predominantly rural. The numerical examples address the relative risks of hazardous materials transportation on the basis of differing assumptions concerning the truck accident rates and volumes on the alternative routes.

Example 1—Use of an Agency's Own Data

Example 1 involves a state highway agency that has used its own truck accident, truck volume, and geometric data to develop locally applicable values for truck accident rates and release probabilities using the procedure presented in the previous section. For illustrative purposes, the California truck accident rates presented in Table 3 and the California release probabilities presented in Table 5 will be used in this example.

Table 8 presents the basic state truck accident data for each route segment and the application of the chi-squared test to determine whether the expected truck accident rate or the site-specific accident rate should be used. For each route segment, the expected number of truck accidents in 3 years is compared with the actual number of truck accidents observed during that length of time. For route segments 1–2, 2–3, 3–5, and 1–4, the calculated value of χ^2 is less than 4.0, indicating that the state's estimate of the expected truck accident rate should be used in preference to the site-specific accident data. The use of the site-specific accident data would be misleading in these cases, because there is no evidence that their deviations from the expected values are not just random. Route Segment 4–5 was expected to experience 43.5 accidents in 3 years, but 65 accidents actually occurred. In this case, the computed value of χ^2 is 10.62, which is substantially greater than 4.0 and which is highly statistically significant. For this segment, the state should use the site-specific accident rate of 2.37 accidents/million veh-mi computed from Equation 10, rather than the expected value of 1.59 accidents/million veh-mi.

Table 9 presents the application of the recommended revisions to the DOT risk assessment method. Accident probabilities for each route segment in the revised method are determined as the product of the expected state truck accident rates developed in Table 8, the release probabilities from Table 5, and the route segment lengths. The accident consequences are represented by the number of persons potentially exposed to hazardous materials releases per unit length, calculated from the population density along the route segment and the impact zone width. In this case, an impact zone width of 0.5 mi on either side of the roadway was selected.

The population risk for each route segment in Table 9 is computed as the product of the accident probability and the number of persons exposed per unit length. The total population risk for each route is the summation of the risks for each of the individual segments that make up the route. The results (in Table 9) indicate that Route A involves slightly less risk than Route B. Route A would be the preferred route for hazardous materials shipments unless there are qualitative or subjective factors present that favor Route B. Qualitative and subjective factors that may influence the choice between alternative routes for hazardous materials transportation are identified in the DOT guidelines (*1,2*) and include special populations, special property, and emergency response capabilities.

Example 2—Use of Default Accident Rates

Example 2 addresses the same highway network used in the first example, with slight changes to the truck volumes and

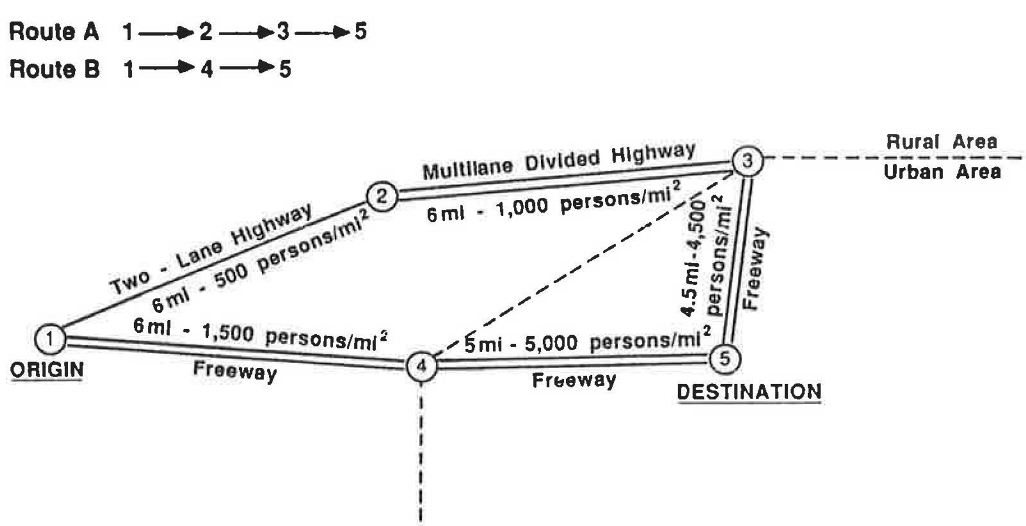

FIGURE 2 Highway network considered in numerical examples.

TABLE 8 COMPARISON OF TRUCK ACCIDENT RATES USING CHI-SQUARED TEST—EXAMPLE 1

(1) Route	(2) Route segment	(3) Area type	(4) Roadway type	(5) Expected truck accident rate (accidents per million veh-mi)[a]	(6) Truck ADT (veh/day)	(7) Length (mi)	(8) Expected number of truck accidents in 3 years[b] (A_e)	(9) Observed number of truck accidents in 3 years (A_o)	(10) Chi-squared statistic[c] (X^2)	(11) $X^2 > 4$?	(12) Truck accident rate for use in risk assessment (accidents per million veh-mi)
A	1-2	Rural	Two-lane	1.73	500	6.0	5.7	7	0.30	No	1.73
	2-3	Rural	Multilane divided	1.23	1,000	6.0	8.1	5	1.19	No	1.23
	3-5	Urban	Freeway	1.59	4,500	4.5	35.3	44	2.14	No	1.59
B	1-4	Rural	Freeway	0.53	1,500	6.0	5.2	9	2.77	No	0.53
	4-5	Urban	Freeway	1.59	5,000	5.0	43.5	65	10.62	Yes	2.37[d]

[a] From Table 1.
[b] From Equation (4).
[c] From Equation (5).
[d] From Equation (10).

TABLE 9 RISK ASSESSMENT FOR HAZARDOUS MATERIALS ROUTING USING REVISED FHWA METHOD—EXAMPLE 1

(1) Route	(2) Route segment	(3) Truck accident rate (accidents per million veh-mi)[a]	(4) Probability of release given an accident[b]	(5) Length (mi)	(6) Release probability[c]	(7) Population density (persons/mi^2)	(8) Impact zone width (mi)	(9) Total persons exposed[d]	(10) Persons exposed per mi[e]	(11) Population risk[f]
A	1-2	1.73	0.100	6.0	1.038	800	0.5	4,800	800	830
	2-3	1.23	0.100	6.0	0.738	1,000	0.5	6,000	1,000	738
	3-5	1.59	0.062	4.5	0.444	5,000	0.5	20,000	5,000	2,218
										3,786
B	1-4	0.53	0.083	6.0	0.264	1,000	0.5	7,000	1,000	264
	4-5	2.37	0.062	5.0	0.735	5,000	0.5	20,000	5,000	3,674
										3,938

ROUTE A INVOLVES LESS RISK THAN ROUTE B

[a] From Table 8.
[b] From Table 5.
[c] Calculated as (3) x (4) x (5) from Equation (7).
[d] Calculated as (7) x (5) x (8) x 2.
[e] Calculated as (9)/(5).
[f] Calculated as (6) x (10).

accident experience on some of the route segments. This example illustrates the use of the default truck accident rates and release probabilities in Table 6.

Table 10 presents the basic accident data for each route segment and application of the chi-squared test. The calculated values of χ^2 for route segments 2–3, 3–5, and 1–4 are less than 4.0, as in the first example, indicating that the default truck accident rate should be used rather than the site-specific accident rate. As in the first example, the calculated value of χ^2 for route segment 4–5 is greater than 4.0, indicating that the site-specific accident rate should be used rather than the default value.

Route Segment 1–2 in Table 10 represents an important exception to the chi-squared test. This route segment is expected to experience only 2.9 truck accidents in a 3-year period. The chi-squared test is not applicable when the expected number of truck accidents (A_e) is less than 5, so the alternative test based on the Poisson distribution should be used. Interpo-

TABLE 10 COMPARISON OF TRUCK ACCIDENT RATES USING CHI-SQUARED TEST—EXAMPLE 2

(1) Route	(2) Route segment	(3) Area type	(4) Roadway type	(5) Expected truck accident rate (accidents per million veh-mi)[a]	(6) Truck ADT (veh/day)	(7) Length (mi)	(8) Expected number of truck accidents in 3 years[b] (A_e)	(9) Observed number of truck accidents in 3 years (A_o)	(10) Chi-squared statistic[c] (X^2)	(11) $X^2 > 4$?	(12) Truck accident rate for use in risk assessment (accidents per million veh-mi)
A	1-2	Rural	Two-lane	2.19	200	6.0	2.9	8	d	Yes[d]	6.09[e]
	2-3	Rural	Multilane divided	2.15	1,000	6.0	14.1	9	1.84	No	2.15
	3-5	Urban	Freeway	2.18	4,500	4.5	48.3	55	0.93	No	2.18
B	1-4	Rural	Freeway	0.64	1,500	6.0	6.3	9	1.16	No	0.64
	4-5	Urban	Freeway	2.18	5,000	5.0	59.7	76	4.45	Yes	2.77[e]

[a] From Table 6.
[b] From Equation (8).
[c] From Equation (9).
[d] Chi-squared test is not applicable because $A_e < 5$. Therefore, A_o is compared to a critical value of the Poisson distribution (6.8), as interpolated from Table 7.
[e] From Equation (10).

lation in Table 3 indicates that the critical value of the Poisson distribution is 6.8 accidents when $A_e = 2.9$. Because this route segment experienced more than this critical number of accidents in 3 years, the site-specific accident rate, computed in accordance with Equation 10, has been used rather than the default value.

Table 11 presents the application of the revised FHWA risk assessment procedure to the data for the second example. These calculations are entirely analogous to those for the first example in Table 9. The results indicate that, for the conditions in the second example, Route B involves slightly less risk than Route A. Route B would be the preferred route for hazardous materials shipments unless there are qualitative or subjective factors that favor Route A.

CONCLUSION

The accident probability portion of the DOT hazardous materials routing guidelines can be realigned to more realistically address the likelihood of accidents involving hazardous materials releases. Equation 7 provides the recommended method for determining the relative probability of a hazardous materials release for shipments on a particular route segment. The key elements in the revised guidelines are explicit consideration of (a) the truck accident rates and (b) the probability of a release given an accident. Truck accident rates are more directly applicable to the risk of accidents involving hazardous materials-carrying vehicles than the all-vehicle accident rates used in the current FHWA guidelines. Furthermore, the inclu-

TABLE 11 RISK ASSESSMENT FOR HAZARDOUS MATERIALS ROUTING USING REVISED FHWA METHOD—EXAMPLE 2

(1) Route	(2) Route segment	(3) Truck accident rate (accidents per million veh-mi)[a]	(4) Probability of release given an accident[b]	(5) Length (mi)	(6) Release probability[c]	(7) Population density (persons/mi^2)	(8) Impact zone width (mi)	(9) Total persons exposed[d]	(10) Persons exposed per mi[e]	(11) Population risk[f]
A	1-2	2.19	0.086	6.0	1.130	800	0.5	4,800	800	904
	2-3	2.15	0.082	6.0	1.058	1,000	0.5	6,000	1,000	1,058
	3-5	2.18	0.062	4.0	0.608	5,000	0.5	20,000	5,000	3,041
										5,003
B	1-4	0.64	0.090	6.0	0.346	1,000	0.5	7,000	1,000	346
	4-5	2.77	0.062	5.0	0.858	5,000	0.5	20,000	5,000	4,290
										4,636

ROUTE B INVOLVES LESS RISK THAN ROUTE A

[a] From Table 10.
[b] From Table 6.
[c] Calculated as (3) x (4) x (5) from Equation (7).
[d] Calculated as (7) x (5) x (8) x 2.
[e] Calculated as (9)/(5).
[f] Calculated as (6) x (10).

sion of hazardous materials release probabilities, which vary markedly between accident types, makes the revised procedures more sensitive to differences in accident patterns between highway types (e.g., freeway versus nonfreeway).

The revised procedures are equally applicable to routing decisions based on a highway agency's own truck accident data and decisions based on the default values of truck accident rate and release probability presented here. The use of truck accident rates based on an agency's own data is generally preferable, because these values will be most suited to local conditions.

Default values of truck accident rate and hazardous materials release probability can be developed from existing state data bases of truck accident and exposure data. Data bases containing traffic accident records, ADT volumes, and the percentage of trucks for individual highway segments that can be linked together by a common location identifier (e.g., a milepost system) have been developed by a number of state highway agencies. Default estimates of truck accident rate and hazardous materials release probability have been developed from data for the entire state highway systems of three states.

Site-specific accident data must be used cautiously when the available accident sample sizes for a particular route segment are small, as they often are. The chi-squared test has a key role in the decision to use either the default value of truck accident rates or the truck accident rates based on site-specific data for any given route segment. In the special case where the expected number of truck accidents is less than 5, a test based on the Poisson distribution should be used in place of the chi-squared test.

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