Statistical Evaluation of Population Data For Calculation of Radioactive Material Transport Accident Risks

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Population, Radioactive Material Transport Accident Risks

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Abstract

Calculation of accident dose-risk estimates with the RADTRAN code requires input data describing the population likely to be affected by the plume of radioactive material (RAM) released in a hypothetical transportation accident. In the existing model, population densities within ½ mile (0.8 km) of the route centerline are tabulated in three ranges (Rural, Suburban and Urban). These population densities may be of questionable validity since the plume in the RADTRAN analysis is assumed to extend out to 120 km from the hypothetical accident site. We present a GIS-based population model, which accounts for the actual distribution of population under a potential plume, and compare accident-risk estimates based on the resulting population densities with those based on the existing model. Results for individual points along a route differ greatly but the cumulative accident risks for a sample route of a few hundred kilometers are found to be comparable, if not identical. We conclude, therefore, that for estimation of aggregate accident risks over typical routes of several hundred kilometers, the existing, simpler RADTRAN model is sufficiently detailed and accurate.

Key Words: Accident risk, population distribution, RADTRAN, transportation, radioactive materials

Introduction

A hypothetical radioactive material (RAM) shipment accident may result in a partial release of the contents of one or more packagings in the shipment, in the form of an aerosol, which is dispersed by prevailing wind and diffusion. Any dispersion model can be employed to calculate the time-integrated concentration (TIC) of released aerosol as a function of azimuth angle and distance from the source. Because the location of a potential transportation accident cannot be predetermined, and measurement of frequency distributions of wind direction and speed (wind roses) is not economically feasible for all, or even a comprehensive set of, points along the multitude of possible routes employed in RAM transport, application of such a model is necessarily different from applications to fixed sites. The subject of RAM aerosol dispersion for potential transportation accidents has been addressed in a more general, approximate manner in RADTRAN, a code incorporating applicable models and types of data for the estimation of incident-free doses and accident dose-risks [1].

In RADTRAN, wind-direction dependence is eliminated by the assumption that the density of potentially-exposed population is independent of azimuth angle about a hypothetical accident site. Wind speeds and instability conditions are approximated for all accident locations by a distribution of six Pasquill stability categories (and their minimum applicable wind speeds) representing a conservative average for the Continental U.S. (More conservative or better approximations to local weather can be used in RADTRAN if desired and available.) The results of dispersion calculations, with parameters for the six meteorological stability classes, have been incorporated into the RADTRAN code in the form of tabulated TICs and areas of elliptical contours circumscribing specified TIC ranges (isopleths). Accident dose-risks are calculated for population densities, as defined by distance-weighted averages in three density ranges, encountered within ½ mile (0.8 km) of the centerline of a route.

This model has been criticized as being too general and not taking proper account of large populations in urban areas which lie along most RAM transport routes, particularly metropolitan areas along Interstate highways (mandated for spent nuclear fuel shipments [2]). These criticisms could not be addressed generally for all RAM shipments until the advent of geographic information systems (GISs), which are specifically designed to display and process geographically distributed information such as population distributions, highway maps, demographic data, etc.

This paper presents an application of GIS tools and data to a comparative study of a sample Interstate highway route on I70 across the state of Missouri (Figure I). Accident dose-risks were calculated on the basis of two population models: population density within ½ mile (0.8 km) of the route centerline for each kilometer of the route (419 values), and population density specific to each of 18 dispersion isopleths at 29 potential accident sites, along four random wind directions (2088 values). The two sets of dose-risks were compared to ascertain the accuracy of the original, simplified model for calculation of total accident-risk (for the entire test route).

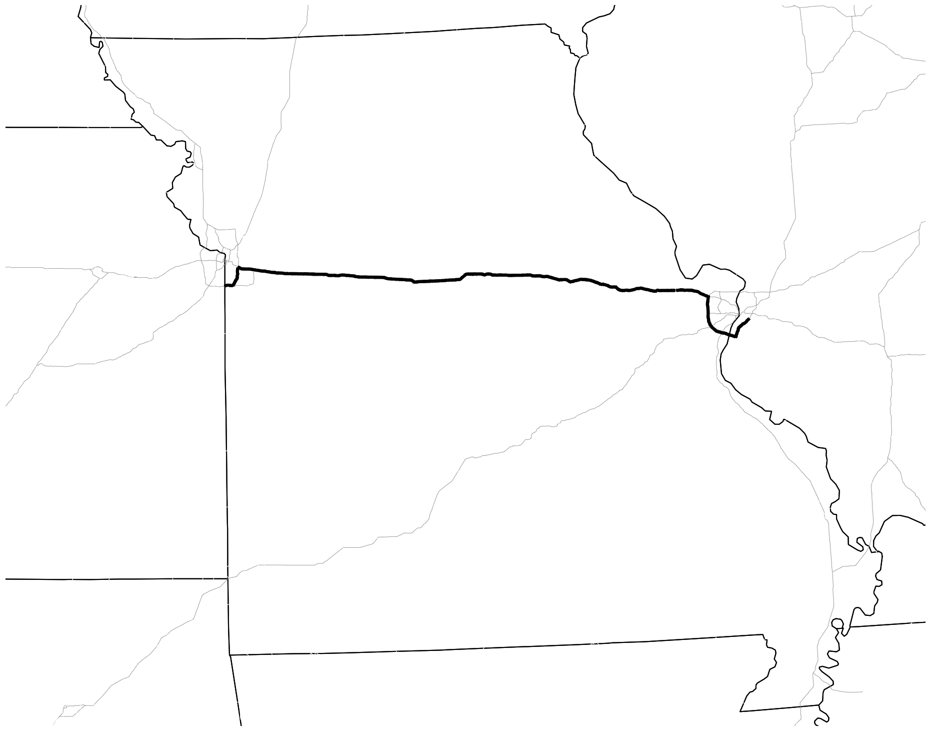

Figure I – Map of I70 Route Across Missouri

Accident Risk Methodology

For estimation of transportation consequences, probabilities and resulting risks associated with transport of RAM, the RADTRAN code [1] has become a standard. In addition to the code documentation available on the Internet, the basic methodology of the code has been described in a previous article [3]. Details of the population model and the generalized method of calculating accident dose-risks are presented in the following section. Modification of this method for incorporation of the GIS-based population data is described in the section following that.

Standard RADTRAN Method

In the simplest dispersion model, airborne materials released in particulate or gaseous form at the scene of an accident are dispersed downwind according to the degree of turbulence in the atmosphere. Although other representations are possible, most commonly used mathematical representations of atmospheric dispersion are based on a Gaussian model (Respirable air-borne particulates i.e., activity median aerodynamic diameter of 10 microns or less, and dispersion over distances of many tens of meters are of primary importance in RADTRAN). In Gaussian models for a "puff" release (i.e., for an instantaneous release), the concentration of the material in the puff ideally has a normal Gaussian distribution along the two axes perpendicular to wind direction. With few exceptions, source clouds for releases associated with transportation accidents should be modeled as puff releases. Source clouds for severe fires that might loft material above an accident site are sometimes modeled as cylinders (e.g., the DIFOUT dispersion code [4]). However, adaptations of the Gaussian model for elevated chronic releases such as those used for modeling releases from smokestacks are inappropriate for use in transportation risk analysis.

Persons in the path of such an aerosol cloud (or plume) inhale material as the cloud passes; particulates are deposited in their lungs in proportion to what is called the dilution factor or time-integrated concentration (denoted by the Greek letter **X** and having units of Ci-sec/m^3) of the aerosol. For radioactive materials, the value of **X** at any point downwind of the release site is directly proportional to the total activity of the released aerosol (Q; in Ci) and is inversely proportional to the windspeed (μ, in m/s). One way of describing the behavior of **X** as one moves away from the release site is to tabulate values of **X**/Q for a given ū versus downwind distance or versus isopleth area. Isopleths are areas enclosed within lines connecting points of equal **X**/Q. They essentially give a "plan view" of downwind dispersion. Because a release becomes increasingly diluted as it travels downwind, isopleths for high values of **X**/Q are nested within isopleths for smaller values for a ground-level release; they are elliptical in shape. With an elevated release, the area of highest **X**/Q is displaced some distance downwind.

The shapes (ratio of major axis to minor axis) of the isopleths vary with atmospheric stability. Atmospheric stability, as classified by Pasquill, ranges from Extremely Unstable (Class A) to Moderately Stable (Class F) [5]. The shape of the Gaussian distribution describing the concentration of material in the downwind cloud also changes with atmospheric stability, becoming broader as conditions become more unstable. This subject is reviewed by Till and Meyer [6] and Turner [7].

Data for atmospheric dispersal may be provided to RADTRAN in two ways. The first is to use a single table of isopleth areas (RADTRAN variable AREADA) and **X**/Q values (RADTRAN variable DFLEV) to characterize average or typical dispersal (Table I). DFLEV values are for a unit source; that is, Q = 1 Ci. Values representing national average meteorology for 18 downwind areas, which are supplied by RADTRAN for this option, are taken from Turner [7]. Alternatively, this table may be filled in with data generated by any dispersion code for any number of areas (RADTRAN variable NAREAS) from a minimum of 2 up to a maximum of 30. The second data-entry option also involves default data but the combination of Pasquill stability conditions may be defined by the user. The first method was employed in this study.

A limitation that applies to both options is that the atmospheric dispersal models on which they are predicated use idealized representations of topography and wind behavior. A strength of both options is that the idealizations are generally conservative for dose calculation. That is, they neglect factors such as surface roughness and shifting wind directions, that promote dilution and dispersion.

After performing an iterative correction to the **X**/Q values for deposition of aerosol material out of the cloud, the tabular RADTRAN dilution factors are integrated over all downwind areas. This value of Integrated Factors is then multiplied by a population density and other parameters to calculate, e.g., the integrated population dose from direct inhalation of dispersed material. The details of this calculation and of other components of the total dose are described in the RADTRAN Technical Manual [9]. **The important point, here, is that in this calculation, the integration is independent of the population density, which is a constant.**

Table I - Isopleth Areas, Centerline Distances and Time-Integrated Concentrations for National Average Meteorology

AREADA (m^2)	CLINE (km.)	DFLEV (TIC)*
4.590E+02	0.0334	3.420E-03
1.530E+03	0.0680	1.720E-03
3.940E+03	0.105	8.580E-04
1.250E+04	0.244	3.420E-04
3.040E+04	0.360	1.720E-04
6.850E+04	0.561	8.580E-05
1.760E+05	1.018	3.420E-05
4.450E+05	1.628	1.720E-05
8.590E+05	2.308	8.580E-06
2.550E+06	4.269	3.420E-06
4.450E+06	5.468	1.720E-06
1.030E+07	11.136	8.580E-07
2.160E+07	13.097	3.420E-07
5.520E+07	21.334	1.720E-07
1.770E+08	40.502	8.580E-08
4.890E+08	69.986	5.420E-08
8.120E+08	89.860	4.300E-08
1.350E+09	120.878	3.420E-08

*TIC units are (Ci-sec/M**3/Ci-released).

The value of population density employed in all of the applicable dose calculations is the same value as that for the incident-free dose calculation, i.e., the density of population within ½ mile (0.8 km) of either side of the route centerline. As presented more fully in [11], the population-density data were obtained by use of a GIS. For a particular kilometer of the route, the intersection of a rectangle 1.0 km along the route and 1.6 km wide, centered on the route centerline, with U.S. Census Block boundaries is determined. (An example of this selection process is illustrated in Figure II for a single kilometer in the suburbs of St. Louis.) Total population within all of the intersected blocks divided by the total area of the same blocks yields the population density associated with that kilometer. Since the geographic range from which this variable is derived is typically very small compared to the full extent of the dispersion plume (the first method of dispersion modeling, described above, includes an isopleth which extends ~120 km from the source point), some have suggested that this calculation might underestimate the risk . It is to address this concern that the method described in the next section was pursued.

Figure II – Sample GIS Selection of U.S. Census Blocks (within ½ mile of route centerline)

Compilation of Population Data

A portion of a spent nuclear fuel transport route (originally analyzed as part of a repository siting program[10]) was selected as a representative sample for comparison of the methods of calculating accident risk just described. The entire route employs Interstate highways from near the Crystal River nuclear plant in Florida to the Hanford Repository near Richland, WA. The portion of this route along I70 across the state of Missouri (from St. Louis to Kansas City) was chosen for its typical predominance of rural areas and two Interstate loops around the two major cities at either end.

Near-Route (Incident-Free) Population

Population densities within ½ mile (0.8km) of the highway centerline were compiled previously [11] as described above. The individual kilometer values for the Missouri portion were aggregated, in the sequence of their occurrence along the route, into contiguous segments having distance-weighted average population densities falling in one of three ranges employed in RADTRAN route characterization (Rural: 0 to 66 persons/km^2; Suburban: 67 to 1670 persons/km^2; Urban: >1670 persons/km^2 [12]). Twenty-nine segments were identified by this procedure, ranging in length from 1 to 97 km; these segments and their characteristics are listed in Table II in order of occurrence from the IL/MO border on I270, along I70 , to the MO/KS border on I435.

Table II: Properties of 29 Route Segments

ID *	Length (km)	Type**	Average, Near-Route Population Density (persons/km^2)
14.5	28	S	613
29	1	R	0.818
33	7	S	1130
37	1	U	1840
38.5	2	S	443
41	3	R	6.26
44	3	S	824
46	1	U	1670
62.5	32	S	333
83.5	10	R	33.3
89.5	2	S	77.7
95	9	R	41.2
100.5	2	S	210
150	97	R	11.0
207.5	18	S	332
218	3	R	44.6
221	3	S	79.5
271	97	R	7.22
320	1	S	210
336	31	R	7.01
353	3	S	81.5
358.5	8	R	14.1
364.5	4	S	103
370	7	R	31.2
375	3	S	170
377	1	R	28.9
382	9	S	555
387	1	R	28.5
403.5	32	S	549

* Distance of segment center from IL/MO border in km.
** Population-density categories: Rural, Suburban and Urban

Distributed (Dispersion Plume) Population

A set of ellipses, describing the largest 13 of the 18 isopleths employed in RADTRAN for accident analysis (Table I), was overlaid on a GIS map of the route and surrounding U.S. Census blocks. The remaining five are the innermost isopleths, which lie within the smallest of the 13 isopleths used in the GIS set; their dimensions are smaller than or comparable to 0.8 km and U.S. Census block resolution and including them as discrete areas would have introduced an element of precision without accuracy into the calculation. (Figure III illustrates an overlay of a set of

Figure III – Example of Isopleths Overlaid on U.S. Census Blocks

isopleths on U.S. Census Blocks in the vicinity of St. Louis.) One end of the major axis of each isopleth was located at the midpoint of each of the 29 segments listed in Table II with their common major axes oriented along a randomly chosen angle within each of the four compass quadrants (relative to true north). The 29 midpoints and 4 directions (60, 105, 210 and 330 deg.) provide a data set that can reasonably be claimed to be representative of unknown locations and wind directions of hypothetical accidents on this route.

By use of available GIS utilities, either existing or developed, U.S. Census blocks within or touching a selected isopleth were identified; the total population and total area of these blocks were tabulated. For each isopleth, the population and area of the next-smaller isopleth were subtracted and the ratio of the two differences yielded an average population density for the increment in plume area represented by that isopleth:

$$PopDen_n = \frac{Pop_n - Pop_{n-1}}{Area_n - Area_{n-1}}$$

The resulting 13 population densities, together with the single value assigned to the population density of the five smallest isopleths, were then employed in the accident-risk summation described earlier.

Risk Calculations

Accident dose-risks were calculated using RADTRAN 5 and the five different sets of population densities (near route, 60 deg., 105deg., 210deg., and 330 deg.) for each of the 29 route segments; all other input parameters were held constant to emphasize effects of the different population models.

For the Near-Route or standard model, the distance-weighted average of population within ½ mile (0.8 km) of the route centerline was entered into a RADTRAN input file for each segment. The calculated accident dose-risks in person-rem are presented in the column labeled "Nr.-Rte. Risk" in Table III.

For the Distributed or modified model, a set of 18 population density values was entered into a separate RADTRAN input file for each segment and each angle. The results of these 116 calculations (29 segments x 4 angles) are listed under "Distributed Risk" in Table III together with the average and standard deviation of the four values for each segment.

Discussion and Conclusions

Comparison of the Near-Route and average Distributed risk values in Table III, on a segment-by-segment basis, reveals many cases in which there are significant differences. Such differences are not unexpected in view of the wide range of population densities (e.g., towns under a plume extending from a Rural segment) that may be encompassed by isopleths (Table I) extending far beyond 0.8 km from the segment midpoint. However, the total for each angle, and particularly for the Averages, over the entire route across Missouri (at the bottom of Table III), are comparable to the total Near-Route value. This result may be understood by observing that the Near-Route method averages population in a variety of areas along the route while the Distributed method averages population along lines intersecting a limited number of points on the route. In both cases, population densities over extended areas are included in the total route risk calculation.

Histograms and cumulative distributions of the two sets of risk values (Near-Route and Distributed) are plotted in Figures IV and V; the dose-risk bins designate ranges ≤ the value and > the next smaller value. For such small data sets (29 values, each) the distributions are not expected to be smooth yet the plots are visually distinct, as shown in Figure VI. To assess the significance of the difference, the Chi-Squared (χ^2) test for goodness of fit was applied to the two distributions. The intervals, counts and pertinent χ^2 values are listed in Table IV; intervals were selected to cover the data ranges uniformly and to provide at least 5 counts in each interval. The calculated value of χ^2 is clearly less than the test value, indicating that the two distributions are statistically the same.

The example analyzed in this paper indicates that, for risk analyses of RAM transport routes that are hundreds of kilometers or more in length, the existing RADTRAN model of population distribution for accident-risk calculation yields results which are accurate to within the general accuracy of the calculations (~2x). This level of uncertainty is readily addressed quantitatively through application of existing probabilistic techniques already in use with RADTRAN [13]. Thus, one can conclude that more detailed population analysis is not necessary for calculation of accident risks except in cases related to isolated points on a route or very short (a few km) route segments of special interest.

Table III – Calculated Risks for Near-Route and Distributed Population Data

	Nr.-Rte.	Distributed Dose-Risk (person-rem)					
ID	Dose-Risk	60deg	105deg	210deg	330deg	Average	Std. Dev.
14.5	1.99E-03	2.71E-03	1.14E-03	4.25E-04	1.02E-03	1.32E-03	9.76E-04
29	7.38E-08	5.71E-05	5.76E-05	2.31E-05	1.51E-05	3.82E-05	2.23E-05
33	9.17E-04	3.29E-04	6.81E-04	3.66E-04	3.89E-04	4.41E-04	1.62E-04
37	1.22E-05	4.08E-06	6.45E-06	5.22E-06	2.12E-06	4.47E-06	1.84E-06
38.5	1.03E-04	1.39E-04	1.75E-04	1.52E-04	7.24E-05	1.35E-04	4.41E-05
41	1.69E-06	8.71E-05	1.46E-04	3.52E-05	4.52E-05	7.84E-05	5.04E-05
44	2.87E-04	9.14E-05	1.55E-04	9.10E-05	2.30E-04	1.42E-04	6.60E-05
46	1.11E-05	4.10E-06	5.82E-06	3.35E-06	3.25E-06	4.13E-06	1.19E-06
62.5	1.24E-03	2.21E-03	2.85E-03	4.21E-04	5.37E-04	1.50E-03	1.21E-03
83.5	3.00E-05	1.53E-05	3.39E-04	1.52E-05	1.51E-04	1.30E-04	1.53E-04
89.5	1.80E-05	4.82E-06	7.77E-05	1.91E-05	2.76E-06	2.61E-05	3.52E-05
95	3.34E-05	1.51E-05	2.28E-04	1.61E-05	1.36E-04	9.88E-05	1.03E-04
100.5	4.86E-05	7.05E-06	5.76E-05	2.31E-05	1.12E-05	2.47E-05	2.29E-05
150	9.56E-05	6.33E-05	3.89E-04	4.70E-05	1.46E-03	4.90E-04	6.66E-04
207.5	6.92E-04	4.49E-04	3.58E-04	1.31E-03	3.14E-04	6.08E-04	4.72E-04
218	1.21E-05	9.51E-06	7.18E-05	3.28E-06	4.52E-05	3.24E-05	3.21E-05
221	2.76E-05	9.37E-06	5.09E-05	8.24E-06	4.12E-05	2.74E-05	2.19E-05
271	6.31E-05	4.23E-05	5.22E-05	1.56E-04	1.46E-03	4.28E-04	6.90E-04
320	2.43E-05	1.56E-06	1.81E-06	1.05E-05	6.52E-07	3.63E-06	4.61E-06
336	1.96E-05	1.53E-05	1.87E-05	1.81E-05	4.67E-04	1.30E-04	2.25E-04
353	2.83E-05	3.74E-06	1.62E-05	3.71E-05	6.47E-06	1.59E-05	1.51E-05
358.5	1.02E-05	5.56E-06	3.80E-05	1.19E-05	1.21E-04	4.41E-05	5.31E-05
364.5	4.78E-05	4.97E-05	1.52E-05	1.91E-05	8.72E-06	2.32E-05	1.82E-05
370	1.97E-05	6.61E-06	5.45E-05	1.33E-05	1.05E-04	4.49E-05	4.53E-05
375	5.90E-05	7.94E-06	1.64E-05	3.18E-05	1.34E-05	1.74E-05	1.02E-05
377	2.60E-06	1.67E-06	1.16E-05	8.59E-06	1.51E-05	9.24E-06	5.70E-06
382	5.79E-04	1.10E-03	3.55E-04	3.11E-04	1.39E-04	4.76E-04	4.26E-04
387	2.57E-06	1.74E-06	2.29E-05	1.51E-05	1.51E-05	1.37E-05	8.79E-06
403.5	2.04E-03	2.17E-03	1.82E-03	7.09E-04	1.98E-03	1.67E-03	6.56E-04
Totals	**8.42E-03**	**9.61E-03**	**9.21E-03**	**4.31E-03**	**8.81E-03**	**7.98E-03**	**6.20E-03**

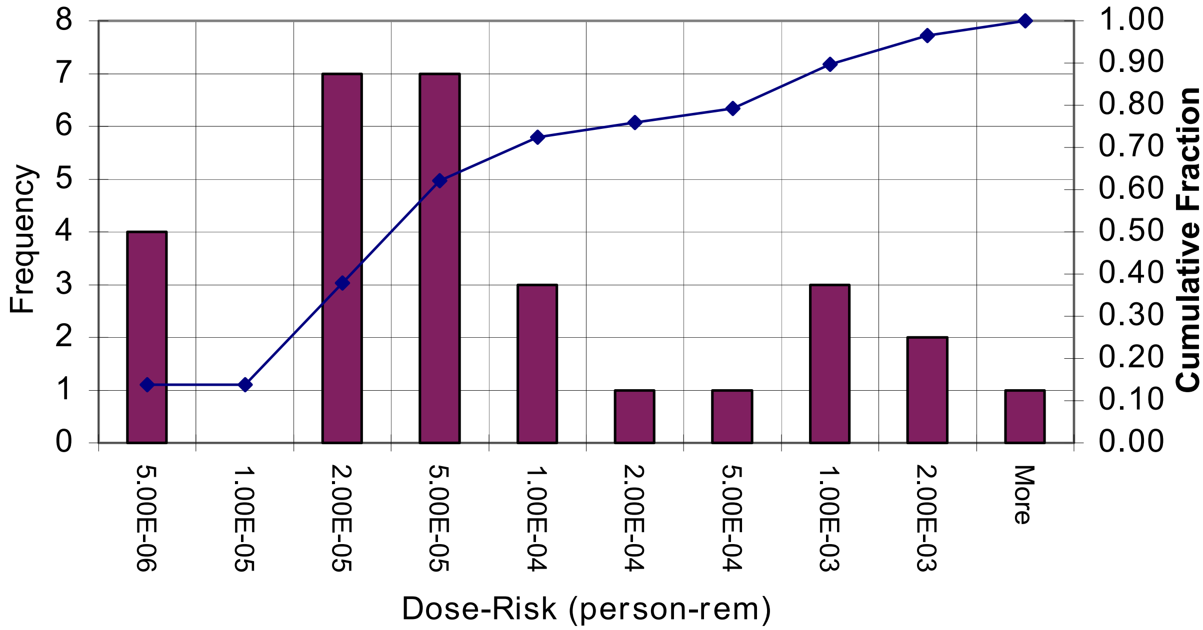

Figure IV – Histogram and Cumulative Distribution of Near-Route Dose-Risk Values in Table III

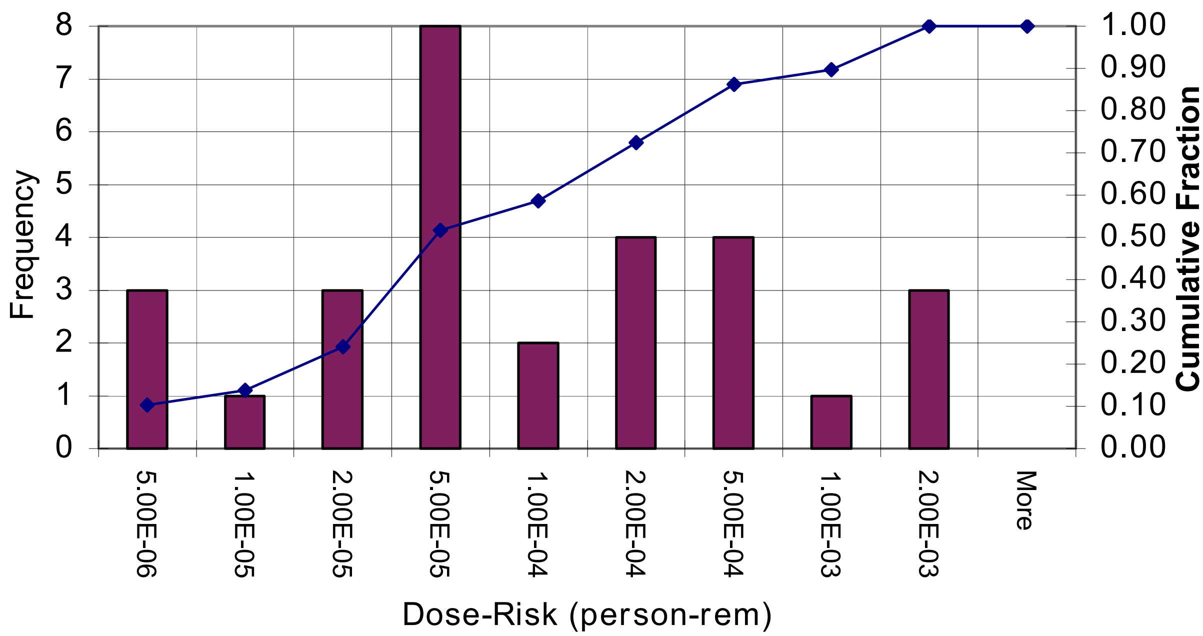

Figure V – Histogram and Cumulative Distribution of Average Distributed Dose-Risk Values in Table III

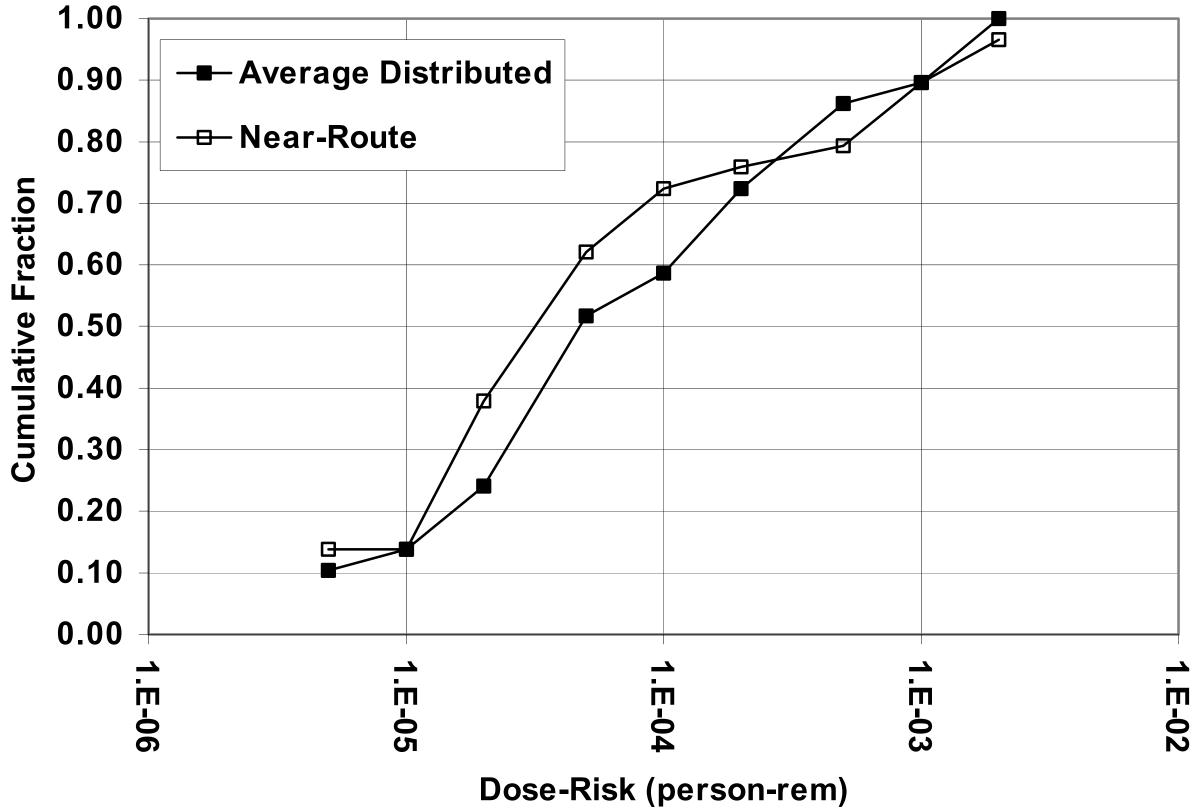

Figure VI – Comparison of Cumulative Distributions in Figures I and II

Table IV – Chi-Squared Test of Distributions of Risks

Interval	Near-Route	Distributed
$\leq$ 2.0E-5	11	7
> 2.0E-5 $\leq$ 2.0E-4	11	14
> 2.0E-4 $\leq$ 2.0E-3	7	8
χ^2 = 16/11 + 9/11 + 1/7 = 2.42		
Value of χ^2 for 2 degrees of freedom, 5% significance = 5.99		

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