SANDIA REPORT

SAND2006-7723
Unlimited Release
Printed: December 2006

Tractor/Trailer Accident Statistics

G. Scott Mills, Jeremy L. Sprung, and Douglas M. Osborn

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia is a multiprogram laboratory operated by Sandia Corporation,
a Lockheed Martin Company, for the United States Department of Energy's
National Nuclear Security Administration under Contract DE-AC04-94AL85000.

Sandia National Laboratories

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

Available to DOE and DOE contractors from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone: (865)576-8401
Facsimile: (865)576-5728
E-Mail: reports@adonis.osti.gov
Online ordering: http://www.osti.gov/bridge

Available to the public from
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Rd
Springfield, VA 22161

Telephone: (800)553-6847
Facsimile: (703)605-6900
E-Mail: orders@ntis.fedworld.gov
Online order: http://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online

SAND2006-7723
Unlimited Release
Printed December 2006

Tractor/Trailer Accident Statistics

G. Scott Mills, Jeremy L. Sprung, and Douglas M. Osborn
Material Transportation Risk Assessment & Security Department
Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185-0718

ABSTRACT

This report describes the analysis that was performed to construct (1) a new truck accident event tree, including the fractional occurrences of route wayside surfaces, (2) new truck accident speed distributions and (3) new estimates of truck accident fire probabilities. The branch point fractions needed to construct the new event tree were calculated using truck accident data for the years 1996 through 2000 and vehicle mileage data for the years 1997 and 2000. Truck accident data was also used to estimate the fraction of bridge accidents that result in the truck falling off of the bridge. A count of bridges on Interstate 95 yielded a conservative estimate of the number of truck accidents that might lead to collisions with very large bridge columns. The occurrence frequencies of route wayside surfaces and surfaces under bridges were developed using Geographic Information System (GIS) databases and methods of analysis.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the contributions of John Cook, Ruth Weiner, and Douglas Ammerman. They would also like to acknowledge the management support of Ken B. Sorenson, David R. Miller, and Jeffrey J. Danneels, as well as the management support by the Office of Nuclear Regulatory Research and the Office of Nuclear Materials Safety and Safeguards of the U. S. Nuclear Regulatory Commission.

Table of Contents

List of Figures

List of Tables

Acronyms

AASHTO	American Association of State Highway and Transportation Officials
DOE	Department of Energy
DOT	Department of Transportation
DU	Depleted Uranium
FARS	Fatality Analysis Reporting System
GES	General Estimates System
GIS	Graphic Information System
LLNL	Lawrence Livermore National Laboratory
MCMIS	Motor Carrier Management Information System
MHE	Most Hazardous Event
NRC	Nuclear Regulatory Commission
OMC	Office of Motor Carriers
ORNL	Oak Ridge National Laboratories
PAR	Police Accident Report
SNF	Spent Nuclear Fuel
SNL	Sandia National Laboratories
STATSGO	State Soil Graphics
TIFA	Truck Involved Fatal Accident
UMTRI	University of Michigan Transportation Research Institute

(This page left intentionally blank.)

1.0 Introduction

Estimation of the risks associated with the transport of spent nuclear fuel by truck is usually done by constructing a representative set of possible truck accidents and estimating the probability of each representative accident and the radiological consequences that would be caused should that accident occur. Construction of an accident event tree is an efficient and powerful way to describe a representative set of accidents. The Lawrence Livermore National Laboratory (LLNL) study titled "Shipping Container Response to Severe Highway and Railway Accident Conditions" [1], which is usually referred to as the Modal Study, contains a truck accident event tree. That event tree was constructed using truck accident data for the years 1973 through 1983. Figure 1 presents the Modal Study truck accident event tree.

Inspection of Figure 1 shows that the Modal Study truck accident event tree first divides truck accident initiating events into two groups:

- Fires, mechanical failures, accidents where the truck overturns, or jackknife accidents where the truck leaves the road and then runs into or hits something.

- Collisions where the truck runs into another vehicle or impacts an on-road structure.

Next, so that an appropriate accident speed distribution can be selected to use in the estimation of truck accident risks, the tree indicates whether the accident occurred: (1) at a highway/railway grade crossing, (2) on level ground (i.e., not on a steep grade), (3) involved in a fall from a bridge, or (4) a plunge down an embankment. Finally the event tree specifies the type of object or surface that the truck runs into or hits, but does not indicate whether this impact initiates fire (As described in Section 8.0 of this report).

This event tree was used in the NUREG/CR-6672 study [2] to support revised estimates of the risks associated with shipping spent nuclear fuel on tractor/semi-trailer rigs. For that study, new estimates of the frequencies of occurrence of Interstate Highway wayside surfaces were developed, but all of the other branch point fractions on the event tree continued to use the values developed for the Modal Study.

Discussion of the NUREG/CR-6672 study at public meetings showed that concerned citizens believed that the Modal Study event tree should be reconstructed using recent truck accident data [3]. This report describes the analysis that was performed to construct:

- A new truck accident event tree, including the fractional occurrences of route wayside surfaces.

- New truck accident speed distributions and new estimates of truck accident fire probabilities.

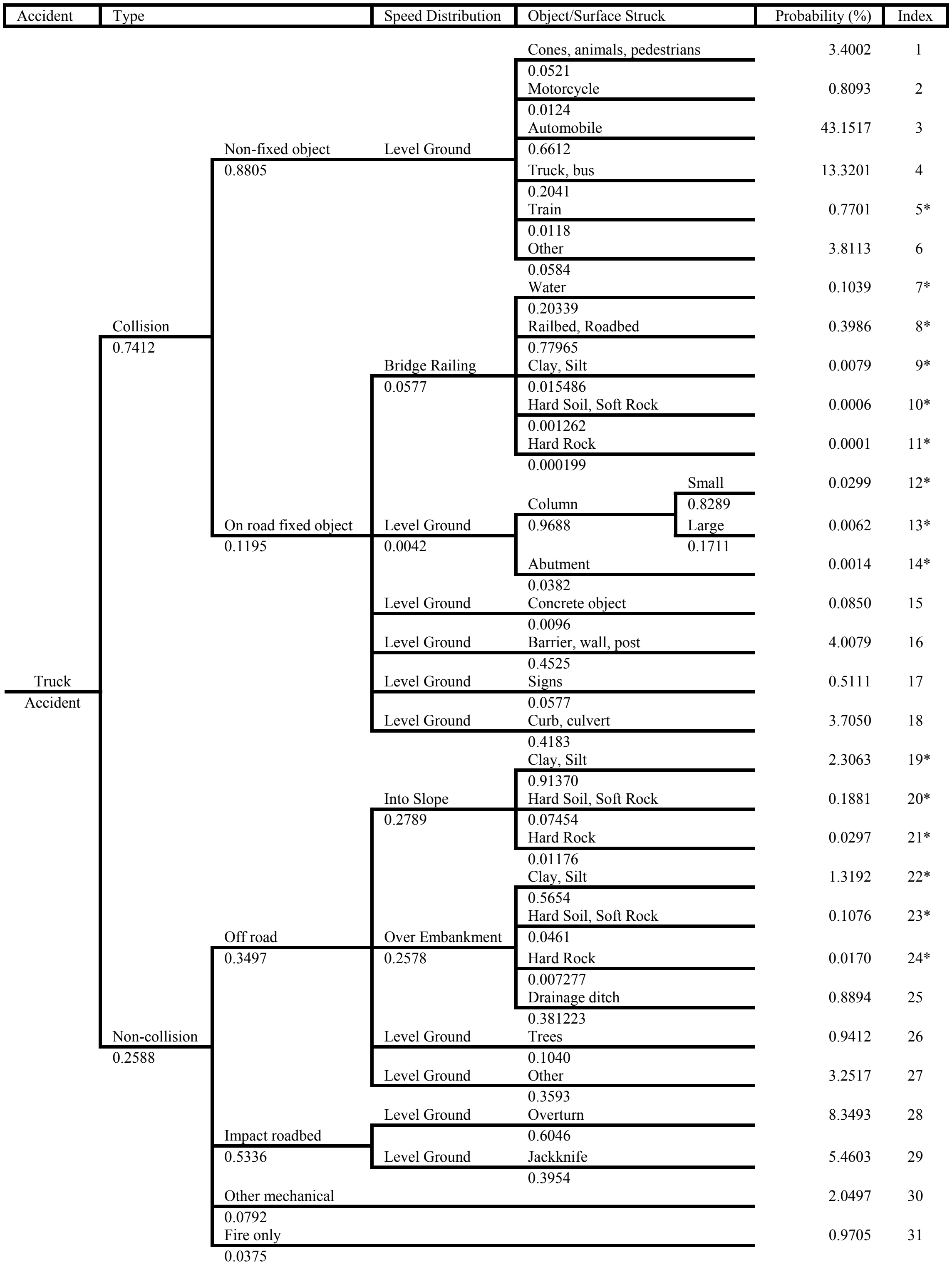

Figure 1: Modal Study truck accident event tree

*Potentially significant accident scenarios.

2.0 Spent Fuel Truck Casks

The shells of almost all modern spent fuel truck casks have either steel-lead-steel walls (e.g., the NAC-LWT truck cask [4]) or steel-DU-steel walls (e.g., the GA-4 truck cask [5]). During transport, these casks, which have a fully loaded weight of about 25 tons, are fitted on both ends with impact limiters. After the spent fuel is loaded into the cask, the cask lid, which is typically equipped with two elastomeric or metallic seals, is attached to the cask body using 12 to 24 one-inch bolts. Typical thicknesses for the three metal shells of steel-lead-steel truck casks are 1 inch of outer steel, 6 inches of lead, and 1 inch of inner steel [6], and 1 inch of outer steel, 3 inches of depleted uranium (DU), and 0.5 inches of inner steel [7] for steel-DU-steel truck casks.

To receive a certificate of compliance from the NRC, a spent fuel cask must be able to remain leak tight ($\leq 10^{-7}$ cm^3/s at 1 atmosphere) after the following tests [8]:

1. A drop of 9 meters onto an unyielding surface, when the cask is equipped with impact limiters.

2. A puncture test consisting of a 1 meter drop onto a 6 inch diameter mild steel bar.

3. Exposure to a 30 minute, fully engulfing, 800 °C pool fire.

4. Immersion in 15 meters of water for not less than eight hours.

The unyielding surface impact speed after a nine-meter drop is 30 miles per hour. The impact speed does not seem to be a very high; however, the surfaces struck during real accidents are almost always yielding surfaces. Yielding surface impacts must occur at speeds much larger than 30 mph, if they are to subject the cask to the same forces that it experiences during a 30 mph impact onto an unyielding surface. The yielding surface will absorb a substantial portion of the impact energy, which in turn greatly reduces the energy available to cause damage to the cask.

For an accident to cause a spent fuel cask to release some of its radioactive contents to the environment, some of the spent fuel rods in the cask and either the cask seals or the cask shell must fail. Dynamic finite element impact simulations suggest that generic steel-lead-steel and steel-DU-steel truck casks fitted with elastomeric seals, but not equipped with impact limiters, are not failed by a 90 mph center of gravity-over-corner (CG/corner) impact onto an unyielding surface [9]. For example, the NAC-LWT steel-lead-steel truck cask equipped with impact limiters is predicted to survive a 90 mph CG/corner impact onto an unyielding surface [10] without the loss of cask containment.

3.0 New Event Tree Structure

Because truck casks are so massive and robust, only a high-speed impact into a massive object with a very hard surface (e.g., a train, a hard rock outcrop, a very large steel reinforced concrete Interstate Highway flyover support column) can threaten the integrity of the cask's containment. Thus, the collision accident paths (scenarios) on the Modal Study event tree that lead to the truck striking:

- A small and/or not very strong fixed object (e.g., small columns, abutments, barriers, walls, posts, signs, trees),

- A small and/or relatively soft non-fixed object (e.g., cones, animals, pedestrians, motorcycles, automobiles), or

- A yielding surface (e.g., soft rock, hard soil, clay, silt, soil, water),

and several non-collision paths (e.g., mechanical failures, truck jackknifes, truck overturns) pose no threat to the containment integrity of a spent fuel truck cask. Consequently, as is shown in Figure 2, the new truck accident event tree constructed by this study combines many of the non-threatening paths on the Modal Study event tree, thereby producing a simpler structure for the new truck accident event tree.

A comparison with the new event tree structure (Figure 2) from the Modal Study event tree structure (Figure 1) shows several differences. The six sub-branches for collisions with a non-fixed object (paths 1 through 6 in Figure 1) have been restructured into four branches as follows:

1. Trains (the only non-fixed object large enough to threaten the containment integrity of a spent fuel cask during a collision)

2. Gasoline tank-trucks (not important for collisions but important for fire scenarios initiated by a collision)

3. Other vehicles (motorcycles, cars, other trucks)

4. Other small non-fixed objects (e.g., cones, animals, pedestrians)

All collisions with fixed objects now appear as sub-branches of a single branch, "Collision with a fixed object." The sub-branches of the "Collision with a fixed object" branch of the Modal Study tree (paths 7 through 18 in Figure 1) have been restructured. The bridge railing and column and abutment branches of the Modal Study event tree are now treated as possible outcomes of bridge accidents, which are now divided into accidents that lead to falls from the bridge and accidents that lead to collisions with bridge components (columns, abutments), but not a fall from the bridge. Structures less massive than columns and abutments (e.g., buildings, walls) have been combined into a single path (path 12 in Figure 2), and all collisions with small fixed objects (trees, signs, barriers, posts, guard rails) have been combined into a single path (path 13 in Figure 2).

On the new event tree, accidents in which the truck slides along the ground, perhaps into a culvert or a ditch, have been combined into a single path (path 14 in Figure 2). All non-collision paths that don't involve fires (e.g., mechanical problems, truck jackknifes or overturns) have been combined into a single pathway (path 19 in Figure 2). The descriptors of the Surface Struck branches, called "Hard Soil, Soft Rock" and "Clay, Silt" in Figure 1 have been changed to "Soft Rock, Rocky Soil" and "Other Soils, Clay, Silt" in Figure 2 because even a very high speed impact onto hard soil poses no threat to a spent fuel cask, while after soil compaction has occurred impact onto rocky soil may lead to significant cask damage.

The "Over Embankment" branch on the Modal Study tree (paths 22 through 25 in Figure 1) has been eliminated because, as is discussed in Section 8.1 (Speed Distributions), the cask impact speed for these accidents should be bounded by the initial speed of the accident. The initial accident speed should bound the sliding speed because sliding friction should cause the cask (or the truck that is carrying the cask) to slow down, rather than accelerate as it slides along the ground or down a slope. Therefore, since there is no good way to estimate the actual sliding speed of a truck or a cask, elimination of this event tree branch causes this set of accidents to be apportioned into branches 14 through 17 in Figure 2. For these branches in Figure 2, use of the initial accident speed to characterize the severity of the cask impact leads to an overestimate of cask damage.

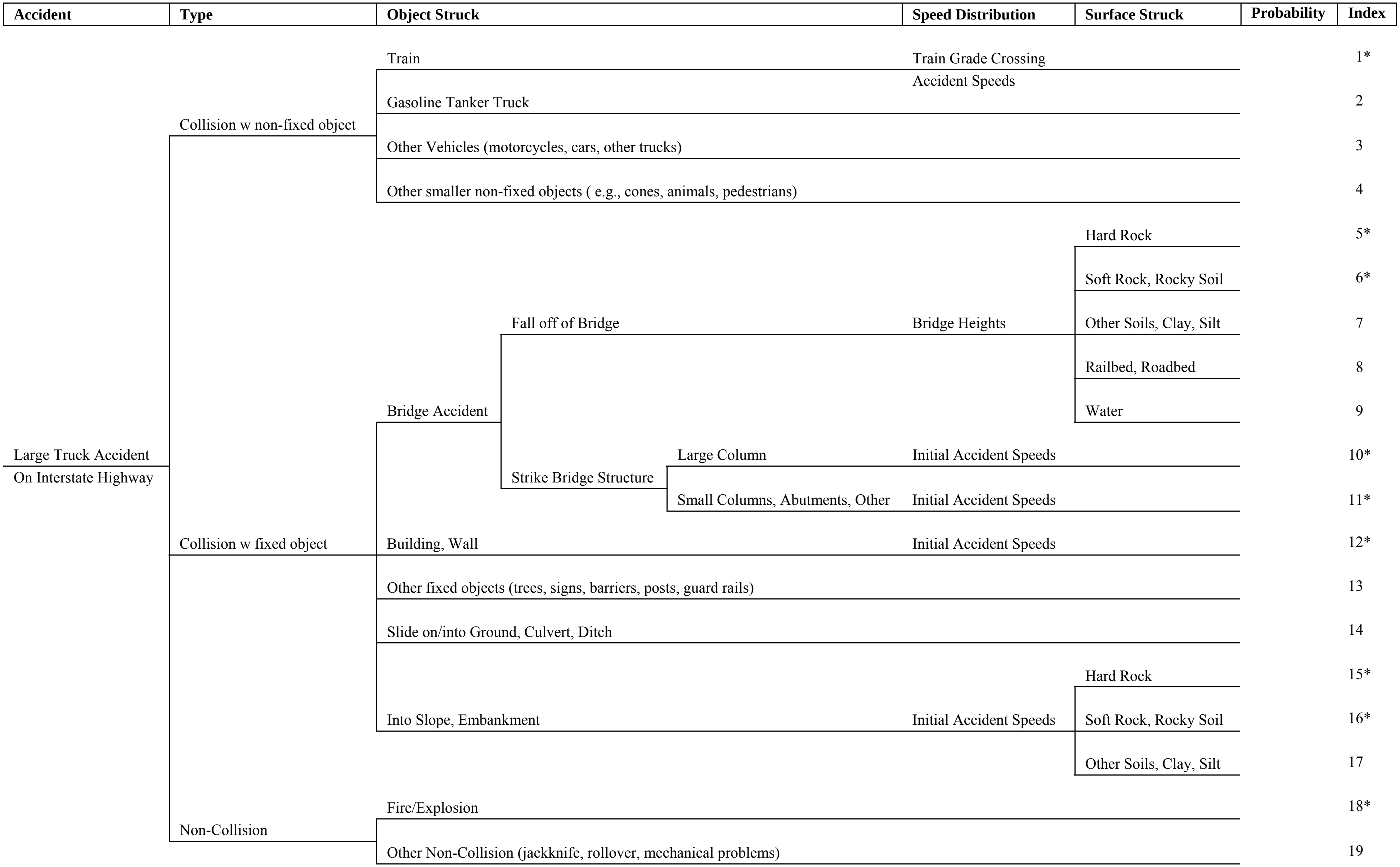

Figure 2: New truck accident event tree structure

*Accident scenarios that might lead to cask failure (loss of containment)

4.0 Database Review

Three primary highway accident databases maintained by the U.S. Department of Transportation (DOT) were considered for development of the new heavy-truck accident statistics:

- Fatality Analysis Reporting System (FARS) [11]

- General Estimates System (GES) [12] databases, maintained by the National Highway Traffic Safety Administration,

- Motor Carrier Management Information System (MCMIS) crash file [13], that is compiled by the Analysis Division of the Federal Motor Carrier Safety Administration (previously named the Office of Motor Carriers)

The MCMIS crash file is often used to support truck safety analysis because it contains only truck accident data and allows accidents to be sorted by truck type (e.g., tractor/trailers) and by accident consequences (e.g., injuries, fatalities, property damage above a reporting threshold). For accidents resulting in a fatality, the Fatality Analysis Reporting System (FARS) database, which is constructed by state analysts, provides more detail about vehicle configuration and significantly more information about crash circumstances and consequences than the MCMIS crash file.

The data in the GES database is extracted from a representative national sample of accidents selected from all of the accidents described in police accident reports. The selected police accident reports (PARs) all describe accidents involving at least one vehicle traveling on a traffic-way that lead to injury, death, or property damage above a reporting threshold.

The annual number of truck accidents resulting in fatalities is available from both the FARS and MCMIS databases. Table 1 presents fatal truck accidents for the years 1997 through 1999 for each of the lower 48 states and the District of Columbia. Table 1 shows that the number of fatal truck accidents tabulated in the FARS database is usually significantly larger than the number tabulated in the MCMIS crash file (about 23% higher on average), and the percent differences [100 × (FARS value − MCMIS value)/(FARS value)] vary greatly from one state to another. An analysis of FARS and MCMIS data by the DOT Volpe Center [14] concluded that the MCMIS data either is incomplete or, because of differing reporting methods, is inconsistent from state to state. Therefore despite the broader coverage of truck accidents, the MCMIS database may not provide a reliable picture of truck accident characteristics on a national perspective. The FARS database also may not provide a reliable picture of truck accident characteristics because the FARS database covers only accidents that involve a fatality and because many severe truck accidents do not involve fatalities. The most accurate data for this study were therefore statistical samples of truck accidents contained in the GES database.

Several other DOT traffic safety statistics tabulations, crash profiles and reports (e.g., "LARGE TRUCK CRASH FACTS," Analysis Division, Federal Motor Carrier Safety Administration, U.S. Department of Transportation, 1999-2001) were reviewed for use in this study. However, the review revealed that each was incomplete with regard to some information important for the performance of this study. The University of Michigan Transportation Research Institute (UMTRI) [15] reports were also reviewed, but were found to be based primarily on fatal accidents and thus not to be a useful source of supplementary data.

Table 1: Comparison of FARS and MCMIS Fatal Truck Accident Numbers

State	FARS 1997	MCMIS 1997	Percent Difference	FARS 1998	MCMIS 1998	Percent Difference	FARS 1999	MCMIS 1999	Percent Difference
Alabama	166	161	3.00%	149	156	-4.70%	143	147	-2.80%
Arizona	72	35	51.40%	98	44	55.10%	108	43	60.20%
Arkansas	113	49	56.60%	105	109	-3.80%	92	71	22.80%
California	369	164	55.60%	365	151	58.60%	319	173	45.80%
Colorado	75	39	48.00%	52	43	17.30%	60	58	3.30%
Connecticut	23	23	0.00%	29	33	-13.80%	22	23	-4.50%
Delaware	15	14	6.70%	18	19	-5.60%	10	10	0.00%
District of Columbia	3	3	0.00%	1	1	0.00%	2	1	50.00%
Florida	284	176	38.00%	317	209	34.10%	327	239	26.90%
Georgia	218	182	16.50%	195	158	19.00%	220	0	100.00%
Idaho	30	30	0.00%	23	26	-13.00%	25	23	8.00%
Illinois	166	126	24.10%	185	155	16.20%	193	174	9.80%
Indiana	159	128	19.50%	179	126	29.60%	191	169	11.50%
Iowa	75	71	5.30%	83	80	3.60%	99	102	-3.00%
Kansas	80	75	6.30%	79	73	7.60%	82	71	13.40%
Kentucky	108	114	-5.60%	97	94	3.10%	94	67	28.70%
Louisiana	122	7	94.30%	140	106	24.30%	118	41	65.30%
Maine	21	18	14.30%	21	12	42.90%	25	16	36.00%
Maryland	88	79	10.20%	65	70	-7.70%	57	42	26.30%
Massachusetts	38	39	-2.60%	37	32	13.50%	35	34	2.90%
Michigan	127	119	6.30%	147	140	4.80%	131	135	-3.10%
Minnesota	88	49	44.30%	78	96	-23.10%	86	87	-1.20%
Mississippi	99	1	99.00%	104	67	35.60%	110	95	13.60%
Missouri	139	133	4.30%	155	154	0.60%	155	164	-5.80%
Montana	24	20	16.70%	18	16	11.10%	15	15	0.00%
Nebraska	46	47	-2.20%	41	44	-7.30%	58	60	-3.40%
Nevada	27	8	70.40%	34	10	70.60%	41	37	9.80%
New Hampshire	12	8	33.30%	10	10	0.00%	9	3	66.70%
New Jersey	77	39	49.40%	64	54	15.60%	59	29	50.80%
New Mexico	51	23	54.90%	44	8	81.80%	48	42	12.50%
New York	142	173	-21.80%	134	141	-5.20%	149	122	18.10%
North Carolina	195	134	31.30%	228	192	15.80%	189	145	23.30%
North Dakota	12	14	-16.70%	8	7	12.50%	18	12	33.30%
Ohio	203	103	49.30%	189	80	57.70%	200	107	46.50%
Oklahoma	96	52	45.80%	106	61	42.50%	82	32	61.00%
Oregon	76	72	5.30%	68	66	2.90%	48	57	-18.80%
Pennsylvania	166	174	-4.80%	178	161	9.60%	207	186	10.10%
Rhode Island	2	2	0.00%	3	2	33.30%	9	5	44.40%
South Carolina	89	95	-6.70%	118	134	-13.60%	123	138	-12.20%
South Dakota	15	16	-6.70%	14	14	0.00%	18	21	-16.70%
Tennessee	129	83	35.70%	136	82	39.70%	165	80	51.50%
Texas	410	337	17.80%	422	387	8.30%	384	248	35.40%
Utah	46	54	-17.40%	44	54	-22.70%	41	47	-14.60%
Vermont	15	16	-6.70%	10	9	10.00%	8	6	25.00%
Virginia	117	81	30.80%	109	70	35.80%	107	86	19.60%
Washington	77	56	27.30%	69	46	33.30%	59	66	-11.90%
West Virginia	52	27	48.10%	41	25	39.00%	50	53	-6.00%
Wisconsin	80	82	-2.50%	90	92	-2.20%	74	81	-9.50%
Wyoming	24	27	-12.50%	30	29	3.30%	25	27	-8.00%
Totals	4871	3590	26.30%	4935	3951	19.90%	4898	3693	24.60%

5.0 Scenario Probabilities and Branch Point Fractions

The new event tree presented in Figure 2 contains no statistical information. Although it contains descriptive labels for each of its branches, no branch point fractions are given, and therefore, in the column titled "Probability," there are no accident scenario probabilities associated with the Index numbers that identify the endpoint of each accident path.

The probability of a particular accident scenario is the product of all of the branch point fractions that lie on the scenario path. An example of this would be the following for a given accident:

The probability of a collision with a fixed object = 0.054
The probability the collision is into a slope or embankment = 0.046
The probability the slope or embankment is hard rock (assume initial accident speed) = 0.055

$P_{accident} = 0.054 \times 0.046 \times 0.055 = 0.000137$ Equation 1

Where:

$P_{accident}$ = the probability of a particular accident scenario

Thus, before a particular accident scenario probability can be calculated, the branch point fractions must be determined. Since all of the fractions that comprise a single set of branches must sum to one, fraction values need only to be calculated for all but one of these branches. An example of branch point probability summing would be the following for the branch column titled "Type" (see Figure 2):

The probability of a collision with a non-fixed object = 0.820
The probability of a collision with a fixed object = 0.054
The probability of a non-collision = 0.126

$P_{total} = 0.820 + 0.054 + 0.126 = 1.000$ Equation 2

Where:

P_{total} = the sum of the branch point fractions

The accident path probabilities on the new large truck accident event tree (Figure 2) are all conditional on the occurrence of a large truck accident on an Interstate highway. Each scenario probability specifies the fraction of large truck, Interstate Highway accidents that have the characteristics specified by the set of branch point fractions that define the scenario path. For example, a large truck accident that takes place on a bridge and results in the truck falling off the bridge into the river under the bridge would be an accident described by the accident scenario denoted by Index 9 in Figure 2.

The completed event tree does not contain a value for the probability that a large truck accident will occur on an Interstate Highway. This probability is dependent on the shipment route so that leaving it off the event tree is appropriate, and allows the event tree to be generally conditional on the occurrence of an accident.

6.0 Calculation of Branch Point Fractions

The branch point fractions probabilities needed to complete the event tree in Figure 2 were calculated as follows. All of the fractions in the column titled “Type” and all of the fractions for the first level branches in the column labeled “Object Struck” were calculated using GES data for the years 1996 through 2000 and vehicle mileage data for the years 1997 and 2000. GES data was also used to estimate the branch point fractions for the event tree branch labeled “Fall off of Bridge.” A count of bridges on Interstate 95 yielded a conservative estimate of the branch point fraction for the event tree branch labeled “Large Column.” The occurrence frequencies of route wayside surfaces and surfaces under bridges were developed using Geographic Information System (GIS) databases and methods of analysis. After values had been developed for all of the branch points in Figure 2, scenario probabilities were calculated as the product of all of the branch point fractions on each path. The branch point fractions and path probabilities to the new event tree structure depicted in Figure 2 produced the final version the event tree, which is presented in Section 7.0 as Figure 3.

6.1 Branch Point Fractions Developed Using GES Data

The GES database tabulates accident data in several ways. Accidents are characterized by the “most harmful event” in the accident event sequence and they are also tabulated by accident locations, for example “on a bridge”. Generally, “most harmful event” data was used to develop accident event tree branch point fractions.

Table 2 presents the accident event fractions that were developed using GES “most harmful event” data. Fraction values are presented for “Collisions with Non-Fixed Objects”, “Collisions with Fixed Objects”, and “Non-Collisions.” Several event subtypes within each of these three broad event classes are also shown. Fraction values are presented for each type of accident for each of the five years surveyed. For each type of accident event considered, the average and the standard deviation of the average are presented in the last column of the table. Each broad event class and the event subtype fractions within the broad event sum exactly to one.

Comparison of the event tree branches in Figure 2 to the accident events listed in Table 2 shows the following differences. First, Figure 2 contains one event tree branch, collision with a gasoline tank-truck, for which no value is presented in Table 2. Second, in Figure 2, three pairs of accident event subtypes have been combined into single event tree branches. Thus, on the event tree:

- “Culvert, ditch” + “Ground” (Table 2) = “Slide on/into Ground, Culvert, Ditch” (Figure 2)
- “Guard rail, concrete barrier, crash cushion, curb, post, pole, sign” + “tree, miscellaneous” (Table 2) = “Other fixed objects (trees, signs, barriers, posts, guard rails)” (Figure 2)
- “Wall” + “Building” (Table 2) = “Building, Wall” (Figure 2)

Therefore, for each of these pairs of accident event subtypes, the branch point fraction value needed to complete Figure 2 is the sum of the accident event fractions given in Table 2 for each of the two event subtypes that are combined.

Table 2: Accident Event Fractions Calculated from GES Data

Accident Event	1996	1997	1998	1999	2000	Average ± Std. Dev.
Collisions with Non-Fixed Objects	**0.828**	**0.819**	**0.826**	**0.828**	**0.798**	**0.82±0.013**
Pedestrian, bicyclist, animal, other (non-motorist, object not fixed, no details)	0.072	0.061	0.030	0.055	0.073	0.058±0.017
Motor vehicle in transport, parked motor vehicle	0.928	0.939	0.970	0.945	0.0	0.942±0.017
Railway Train	0.0	0.0	0.0	0.0	0.0	0.0±0.0
Collisions with Fixed Objects	**0.061**	**0.061**	**0.044**	**0.043**	**0.063**	**0.054±0.010**
Bridge structure	0.100	0.031	0.014	0.023	0.153	0.064±0.060
Ground off a bridge	0.0	0.0	0.0	0.0	0.001	0.0±0.0
Culvert, ditch	0.170	0.146	0.355	0.202	0.040	0.183±0.114
Ground	0.004	0.0	0.0	0.195	0.104	0.061±0.087
Guard rail, concrete barrier, crash cushion, curb, post, pole, sign	0.497	0.392	0.450	0.401	0.461	0.440±0.044
Tree, miscellaneous	0.215	0.398	0.085	0.086	0.193	0.196±0.128
Embankment	0.006	0.022	0.091	0.076	0.035	0.046±0.036
Wall	0.008	0.008	0.005	0.017	0.013	0.009±0.007
Building	0.0	0.003	0.0	0.0	0.0	0.001±0.001
Non-Collisions	**0.111**	**0.120**	**0.130**	**0.129**	**0.139**	**0.126±0.010**
Rollover, jackknife, falling object, other, no details	0.932	0.990	0.940	0.975	0.916	0.950±0.031
Fire/explosion	0.068	0.010	0.060	0.025	0.084	0.050±0.031

6.2 Accidents Involving Tanker Trucks

Because the GES database does present down results for truck accidents by the type of vehicle struck, for example, gasoline tank-trucks, a value for the Gasoline Tank-truck branch in the new event tree could not be developed using GES data. However, if involvement in accidents is roughly proportional to the miles driven by any class of vehicles, then a value for this event tree branch can be developed using yearly mileage data for all vehicles, all trucks, and all tanker trucks [16, 17]. Table 3 presents mileage data for each of these three classes of vehicles.

Table 3: Vehicle Mileage (millions of miles)

Vehicle Class	1997	2000
Tanker Trucks	8,604	
All Trucks	1,044,235	1,064,655
All Vehicles		2,631,522

Using the data in Table 3, a value for the Gasoline Tanker Truck event tree branch in Figure 2 can be calculated as follows:

$$f_{\text{tanker trucks}} = f_{\text{all vehicles}}(\text{miles}_{\text{all trucks}}/\text{miles}_{\text{all vehicles}})(\text{miles}_{\text{tanker trucks}}/\text{miles}_{\text{all trucks}}) \qquad \text{Equation 3}$$

Where:

$f_{\text{all vehicles}}$ = 0.942 (Table 2)
$\text{miles}_{\text{all trucks}}$ = 1,064,655 million miles (Table 3 for the year 2000)
$\text{miles}_{\text{all vehicles}}$ = 2,631,522 million miles (Table 3 for the year 2000)
$\text{miles}_{\text{tanker trucks}}$ = 8,604 million miles (Table 3 for the year 1997)
$\text{miles}_{\text{all trucks}}$ = 1,044,235 million miles (Table 3 for the year 1997)

Substitution of these values into Equation 3 yields $f_{\text{tanker trucks}} = 0.003$. Since some tanker trucks carry liquids that are not flammable (e.g., water, milk), this value is somewhat conservative estimate of the fraction of all vehicle collisions that involve a tank-truck that is carrying a flammable liquid. Finally, because:

$$f_{\text{all vehicles}} = f_{\text{tanker trucks}} + f_{\text{other vehicles}} \rightarrow f_{\text{other vehicles}} = 0.942 - 0.003 = 0.939.$$

6.3 Truck/Train Accidents

Although the GES truck accident data for the years 1996 through 2000 show that no truck/train collisions occurred, presumably because there are a limited number of railway grade crossings on Interstate Highways, the value of the Collision with a non-fixed object branch for trains is arbitrarily set to 0.001, the smallest value consistent with reporting values to three significant figures and, in order to keep the sum of the Collision with a non-fixed object branches equal to one, the value of the Other Vehicles branch, the largest sub-branch on this path, is decreased by 0.001 from 0.939 to 0.938.

6.4 Accidents on Bridges

The GES database tabulates accidents that involve a truck collision with a “bridge structure.” Since a collision with a bridge structure usually will not cause the truck that collides with the “bridge structure” to fall off of the bridge, this GES accident event needed to be subdivided into bridge collisions that led to falls from the bridge and bridge collisions that didn’t lead to falls from bridges.

The GES accident database identifies accidents that occur “on a bridge”, accidents where the “vehicle departed roadway” or the “vehicle remained off roadway,” and accidents where the “most harmful event” was a collision with the “ground”, a “culvert or ditch”, an “embankment”, a “bridge structure”, a “guardrail’, or a “concrete traffic barrier or other longitudinal barrier.” Accidents on bridges where the truck left the road or remained off the road and then collided with the ground, a culvert, a ditch, or an embankment were counted as accidents where a fall from a bridge had most likely occurred. Accidents on bridges where the truck left the road or remained off the road and then collided with a bridge structure, a guardrail, or a concrete traffic barrier or other longitudinal barrier were counted as accidents that might have led to a fall from a bridge. Thus, counts of these two sets of truck accidents defined a range for accidents that occurred on bridges that might have led to falls from the bridge. GES accident data for the years 1996 through 2000 were used to develop these counts. Table 4 presents the results of this analysis.

Table 4: Truck Accidents* on Bridges That Result in Falls from Bridges

Year	Bridge Accidents	Falls from Bridges		Fraction of Bridge Accidents that Lead to Falls from the Bridge (range)
		Hit Ground, Ditch, Culvert, Embankment (lower bound)	Hit Ground, Ditch, Culvert, Embankment Bridge Structure, Guardrail, Concrete Traffic Barrier, Longitudinal Barrier (upper bound)	
1996	1045	0	314	0 to 0.30
1997	2050	0	25	0 to 0.012
1998	1017	0	412	0 to 0.41
1999	1243	0	12	0 to 0.0097
2000	846	9	13	0 to 0.015
Average	1240	2	155	0.0016 to 0.125

* Heavy Truck Accidents on Interstate Highways

Table 4 shows that the lower bound estimate for the fraction of bridge accidents that lead to a fall from the bridge is 0.0016 and the upper bound estimate is 0.125. However, in Table 4, the upper bound results for the years 1996 and 1998 seem to be too large when compared to the results for the years 1997, 1999, and 2000. Inspection of the data for these two years showed that the inclusion in the sampled set of accidents for each of these years of one accident from a reporting region where very few accidents were sampled caused that accident to receive a very large weight. This in turn greatly increased the upper bound count for "Falls from Bridges" for that year.

The average ± the standard deviation of all of the weighted accident counts for the five year period 1996 through 2000 that enter column four of Table 4 is 43.1±95.0. Because the two suspect values both lie almost three standard deviations above this average, the values in column four of Table 4 were recalculated dropping these two anomalously high-weighted accident counts. With this adjustment, the upper bound result for the year 1996 changed from 314 to 17, the upper bound result for 1998 changed from 412 to 104, and the average ± the standard deviation of all of the upper bound weighted accident counts changed to 10.7 ± 12.3. Thus, dropping the two anomalously high weighted accident count values seems justified. When this was done, the upper bound value for the fraction of bridge accidents that lead to a fall from the bridge changed from 0.125 to 0.026.

The geometric mean of the original range of values (0.0016 to 0.125) for the fraction of bridge accidents that lead to a fall from the bridge is 0.014. This mean value is smaller but still similar to the upper bound value of 0.026 obtained by dropping the two heavily weighted accident counts from the original dataset. Therefore, a value of 0.02 (the average of 0.014 and 0.026) was chosen as a reasonable, and most likely conservative, estimate of the fraction of all bridge accidents that results in a fall from the bridge. Finally, because:

$$f_{\text{fall off bridge}} + f_{\text{strike bridge structure}} = 1.0 \rightarrow f_{\text{strike bridge structure}} = 1.0 - 0.02 = 0.98.$$

6.5 Collisions with Large Columns

Most manmade structures are too small or not hard enough to act as unyielding targets if struck by spent fuel truck casks. To be unyielding, if struck by a truck cask, a manmade structure must be very hard and about the same size and weight as the truck cask. Thus, the walls of buildings, bridge abutments, and most reinforced concrete columns will all act like yielding objects if they are struck by a truck cask.

The GES database has en `tries for collisions with Buildings, Walls, Concrete Barriers, and Bridge Structures. With the exception of massive bridge support columns, like those that support the large "flyover" spans of California-style freeway interchanges, none of these manmade structures will act as an unyielding object if struck by a spent fuel truck cask. Since the GES database does not break out collisions with massive bridge columns, a value for the "Large Column" branch of the "Bridge Accident" path on the new event tree had to be developed using other data.

A conservative estimate of the fraction of bridge columns on Interstate highway bridges that are "Large Columns" was developed by counting all of the bridges on Interstate 95 between Boston and the Pennsylvania/Delaware state line near Willington, DE and determining the fraction of these bridges that were part of an Interstate Highway interchange. All bridges that went over Interstate 95 and all bridges that carried Interstate 95 over some other feature (e.g., another road, a rail line, a river) were counted. The bridge counts are derived from data taken from an unpublished study performed at Sandia National Laboratories that used a commercial computer atlas, Street Atlas 4.0 [18], to develop its data. Table 5 presents the bridge count results for the portion of Interstate 95 examined.

Table 5: Ratios of Bridges Intersecting Interstates to Total Bridges

State	Interstate Bridges	Total Bridges	Ratio
Massachusetts	4	216	0.02
Connecticut	6	173	0.04
New York	6	109	0.06
New Jersey	4	157	0.02
Pennsylvania	3	202	0.02
Total Route	23	857	0.03

For each state traversed by the portion of Interstate 95 examined, Table 5 lists the number of Interstate highway interchange bridges, the total number of bridges, and the ratio of these two counts. The table also presents these values for all of the bridges along this portion of Interstate 95 (the data labeled "Total Route"). Since the Boston to Wilmington corridor is heavily populated, the ratio (fraction) for the "Total Route**"** is probably higher than the average fraction for all U.S. Interstate Highways. Therefore, since many of the Interstate Highway intersection bridges on this route will not be California-style "flyover" interchanges, the value of 0.03 is believed to be an overestimate (a significantly conservative estimate) of the fraction of bridge columns along Interstate Highways that will be large enough to act as an unyielding target if struck by a spent fuel truck cask.

6.6 Route Wayside Surfaces and Surfaces Under Bridges

The severity of a spent fuel truck collision accident depends principally on the hardness and thickness of the hardest surface that the cask strikes and the speed with which the cask strikes that surface. Therefore, the occurrence frequencies of the surfaces that the cask might strike during a truck accident needed to be developed.

6.6.1 Definition of Surface Layer Depth and Surface Types

Inspection of the event tree structure in Figure 2 shows that occurrence frequencies are needed for the following route wayside surfaces, "Hard Rock", "Soft Rock, Rocky Soil", and "Other Soils, Clay, and Silt"; also for "Water" and "Railbeds and Roadbeds", if the accident involves a fall from a bridge. Comparison of the wayside surface types in Figure 1 to those in Figure 2 shows that the Modal Study wayside surface category "Soft Rock, Hard Soil" has been redefined on the new event tree as "Soft Rock, Rocky Soil". This was done because, when a 16,300 lb OD-1 spent fuel cask was dropped from a height of 2000 ft (230 mph impact speed) onto hard packed high desert soil at a test site near Edgewood NM, the cask penetrated 4.2 ft into the soil without sustaining any significant damage [19]. This suggests that hard soils are too yielding to pose an impact threat to a spent fuel truck cask. Thus, only a high speed impact with a very highly compacted, essentially incompressible, soil layer will be able to damage a truck cask. However, if the cask collides with a rocky soil layer and the impact compresses the soil layer enough to push all of the rocks together, then this rocky soil layer will behave much like a highly fractured layer of rock. Since nearly incompressible hard soils are relatively rare, while rocky soils are common, the Modal Study wayside surface category "Soft Rock, Hard Soil" was redefined to be "Soft Rock, Rocky Soil", in order to better capture the surfaces that posed a risk to a spent fuel truck cask during a high-speed impact accident.

If the surface that the cask strikes first is a fairly thick soil layer, and if the cask does not penetrate this layer because the cask impact speed is too low and/or the layer is too thick, then the properties of this soil layer will be determined by the size and amount of the rocks that are contained in the layer. However, if the surface layer (e.g., a layer of topsoil) is not very thick and is easily penetrated by the cask, then the surface of concern may be the one below this top layer. For example, if the cask strikes a grassy layer of topsoil that is supported by bedrock or by a thick layer of rocky soil, and if the cask easily penetrates this grassy layer of topsoil, then the impact of concern will be with the underlying bedrock or the layer of rocky soil. Similarly, if the cask falls off a bridge into a stream or a shallow river, the shallow water layer will be penetrated and the impact of concern will not be with the water in the stream or the river but with the streambed or the riverbed. Conversely, the water body surface will probably be the impact surface of concern, if the water body is deep enough to be classed as navigable.

If the cask speed and the surface layer's thickness allow the cask to penetrate the layer, during penetration the cask speed may decrease enough so that, even if the underlying layer is unfractured hard rock, the cask will not fail when it penetrates the overlying soil layer and strikes the hard rock layer. Accordingly, in order to identify the frequencies of the Interstate Highway wayside surfaces that are of concern, an estimate was needed for the minimum thickness of an overlying soil layer that will slow a striking cask enough so that any underlying rock layer is not of concern should the cask completely penetrate the soil layer. This thickness estimate was developed as follows.

Ammerman [20, 21] has used experimental data [19, 22, 23] for the end-on impact of very large, heavy, cask-like objects onto hard soils to derive the following empirical expression that relates the impact force, F, in pounds to penetration distance, soil properties, and the dimensions and weight of the impacting object.

$$F = 3.6x10^4 D\left[d^{0.922} - 0.78x10^4\left(e^{-1.5d} - e^{-3d}\right)\right] \qquad \text{Equation 4}$$

Where:

$$\int_0^d Fdx = \Delta E = E_2 - E_1,\ \ E_i = \frac{1}{2}mv_i^2 \qquad \text{Equation 5}$$

D = the diameter of the cask determined from the cross-sectional area of impact (inches)
d = the penetration distance of the cask into the soil layer (feet)
$3.6x10^4$ = the value of the leading constant for dry hard-packed desert soil
m = the mass of the cask (pounds-sec^2/ft)
E_2 = the cask's impact kinetic energy into the soil layer (ft-pounds)
v_2 = the cask's impact velocity into the soil layer (ft/sec)
E_1 = the cask's exit kinetic energy from the soil layer (ft-pounds)
v_1 = the cask's exit velocity from the soil layer (ft/sec)

To calculate a value for d, the energy difference ΔE is set equal to the difference between the striking energy provided by maximum real (historic) accident impact speeds and the cask striking energy needed to cause the cask to fail. If this energy difference is used to calculate a value for d for hard soil, a minimum value will be obtained for d.

Historic truck accident data (see Figure 4) suggests that very few truck accidents will occur at speeds that exceed 90 mph. Finite element analyses documented in NUREG/CR-6672 [24] indicate that, for truck cask impacts onto an unyielding surface, $v_{cask\ failure} \approx 90$ mph. Since both of these speeds are about the same, for this analysis it was assumed that $v_{cask\ failure} = 80$ mph. The solution of the Equations 4 and 5 with $v_2 = 90$ mph and $v_1 = 80$ mph now yielded a hard soil penetration depth of 2.5 ft. as an estimate of the thickness of a layer of hard soil that would be penetrated by a typical 50,000 lb truck cask, if the cask was moving at a speed of 90 mph when it struck the hard soil layer and 80 mph when exited that soil layer.

Since most route wayside surfaces (the ground beside the road, the sides of highway cuts, hillsides, rock outcrops) will have their surfaces oriented more or less parallel to the velocity vector of the truck at the time of accident initiation, most cask impacts onto surfaces will be glancing in nature, and very few will be perpendicular to the struck surface. If one conservatively assumes that impact angles are isotropic, then the most likely impact angle will be 45°. Therefore, if a cask impacts the ground at a speed ≤ 90 mph and an angle ≤ 45°, the cask velocity perpendicular to the ground will be less than 80 mph when it finally contacts a bedrock layer that lies parallel to the ground surface at a depth ≥ 1.8 ft = (2.5 ft)(sin 45°) and consequently loss of containment for the cask will not occur.

This discussion indicates that bedrock that lies more than two feet below (or behind) the route wayside surface will not be of concern because penetration by the spent fuel truck cask through two feet of hard surface soil will consume so much of the cask's impact energy that impact onto a rock layer that lies below or behind this much soil will be unlikely to significantly damage the cask (e.g., cause cask containment to be lost).

As suggested above, a layer of soil that contains rocks (not pebbles) that fill a significant fraction of the layer volume will behave like highly fractured rock once the soil in the layer has been compressed enough to push most of the rocks together. The volume fraction of rocks in a rocky soil that would cause this soil to behave like soft rock when compressed by the impact of a spent fuel truck cask was estimated from the void fraction for typical soils as follows:

Void Volume Fraction = $V_v/(V_v+V_s) = e/(1+e)$ Equation 6

Where:

$e = V_v/V_s$
V_v = the void volume of the soil
V_s = the volume of dirt in the soil.

Table 6 presents literature values [25]. The tabulated values show that soils have an average Void Volume Fraction of about 0.4. If the soil is saturated with water, this void volume will be filled with water and if the soil is dry, it will be filled with air. So the expected void volume of an average soil that contains significant amounts of water might be about 0.2.

Table 6: Soil Void Fractions

Soil Type	V_v/V_s	$V_v/(V_v+V_s)$
Loose uniform sand	0.8	0.44
Dense uniform sand	0.45	0.31
Loose angular-grained silty sand	0.65	0.39
Dense angular-grained silty sand	0.4	0.29
Stiff clay	0.6	0.38
Soft clay[a]	0.9-1.4	0.63
Loess	0.9	0.47
Soft organic clay[a]	2.5-3.2	0.74
Glacial till	0.3	0.23
Average		**0.43**
Expected Value = 0.5*Average		**0.22**

a. Void Fraction calculated using midpoint value for range of e values

Let V_R = the volume of a slice of close-packed 3 inch spheres (e.g., two nested 3x3 layers of spheres) and V_B = the volume of the parallelepiped that just encloses this slice of spheres. If these spheres are rocks, then the volume of dirt (V_D) between the rocks is $V_B - V_R = V_D$. If this dirt volume is increased by the expected void volume of an average soil that contains some water, the volume percentage of rocks in this not yet compacted soil is about 50 percent. Because common rocks have densities of ~2.6 g/cm^3 [26] and common soils have densities that range from 0.7 to 2.1 g/cm^3 (average ~1.6 g/cm^3) [25], a soil that has a volume fraction of rocks of about 50 percent will have a mass fraction of rocks of about 60 percent.

Compression of a rocky soil should begin to increase the resistance of the rocky soil to further compression long before the rocks in the soil reach a close-packed arrangement. Therefore, 25 percent seems a reasonable value for the mass fraction of rock in a rocky layer of soil that will act like a highly fractured layer of rock (that is, like soft bedrock) once the void fraction of the layer has been largely eliminated by compression. Even if fully compressed, a thin layer of rocky soil will provide little resistance to penetration by a spent fuel cask. A rocky layer of soil (or several rocky soil layers) will need to be fairly thick, at least 2 feet, and will need to lie closer to the surface than bedrock, within at most 1 foot to the surface, if impact onto the layer (or set of layers) by a spent fuel cask is to act like impact onto soft bedrock that lies no more than 2 ft below the soil surface. If a single layer of rocky soil must be at least 2 ft thick and must lie within 1 ft of the soil surface, then the bottom of this layer must lie no deeper than 3 ft. This discussion suggests that any wayside surface, that isn't "Hard Rock" or "Soft Rock", will be "Rocky Soil" whenever the mass percent of rocks in the rocky soil layers in the top 3 feet of soil below the wayside surface is ≥ 25 percent, the average diameter of these rocks is ≥ 3 inches, and the sum of the thicknesses of these layers is ≥ 2 ft.

6.6.2 Determination of Surface Types

The occurrence frequencies of "Hard Rock", "Soft Rock", and "Rocky Soil" were developed using the State Soil Graphics (STATSGO) database [27]. The STATSGO database divides the continental United States into a very large number of small geographic areas called Map Units. Each Map Unit has a unique identification number called a "muid" and the location of each Map Unit is specified using a digitized map of the continental United States.

Map Units are subdivided into a number of smaller areas: Each of these subcomponent areas also has a unique identification number. For each Map Unit subcomponent, the STATSGO database tabulates:

- the fractional area of the subcomponent relative to the total area of the Map Unit that contains the subcomponent

- the minimum and maximum depth to coherent, monolithic bedrock formations that must be removed by blasting (i.e., "Hard Rock") and to bedrock that can be removed by a backhoe because it fragments relatively easily (i.e., "Soft Rock")

- the depths of the top and bottom of any layers of "Rocky Soil" that lie above the bedrock

- the percentage by mass of the rocks in each “Rocky Soil” layer that have average diameters (d_{rock}) that fall within a given size range (e.g., $d_{rock} \geq 10$ inches, 10 inches > $d_{rock} \geq 3$ inches)

Given the information available in the STATSGO database and the discussion of significant layer characteristics presented above, the following definitions were adopted for the identification of Map Unit subcomponents that will behave like “Hard Rock”, “Soft Rock”, “Rocky Soil”, or “Other Soils, Clay, Silt”.

- A Map Unit subcomponent was defined to be “Hard Rock”, whenever the average depth to the bedrock that lies below the subcomponent surface was on average ≤ 2 feet and the bedrock could only be removed by blasting.

- If the Map Unit subcomponent wasn’t defined to be “Hard Rock”, then it was defined to be “Soft Rock”, whenever the average depth to the bedrock that lies below the subcomponent surface was on average ≤ 2 feet and the bedrock could be removed by a backhoe.

- If the Map Unit subcomponent wasn’t “Hard Rock” or “Soft Rock”, then it was defined to be “Rocky Soil”, whenever the mass percent of rocks in the rocky soil layers in the top 3 feet of the soil below the subcomponent surface was ≥ 25 percent, the average diameter of these rocks was ≥ 3 inches, and the sum of the thicknesses of these layers was ≥ 2 ft.

- If the Map Unit subcomponent wasn’t “Hard Rock”, “Soft Rock”, or “Rocky Soil”, then it was defined to be “Other Soils, Clay, or Silt”.

These definitions, the STATSGO database and Geographic Information System (GIS) methods of analysis (ARCINFO [28]) were then used to identify Map Units traversed by a set of four representative spent fuel truck shipment routes and to assign a wayside surface type (“Hard Rock”, “Soft Rock”, “Rocky Soil”, or “Other Soils, Clay, or Silt”) to each component of these Map Units.

Exact calculation of the length of a route segment that lies over a specific Map Unit subcomponent could not be performed because the STATSGO database contains the locations of Map Units but does not contain locations for Map Unit subcomponents. Instead, these lengths were estimated by calculating the product of the length of the route that lay over the Map Unit and the fraction of the total Map Unit Area occupied by the subcomponent. Thus, if 10 miles of a route lay over a Map Unit that contained a subcomponent that occupied 30 percent of the area of the Map Unit and the wayside surface definitions developed above caused this subcomponent to be classified as “Hard Rock”, then it was assumed that the subcomponent was traversed by 3 miles of route length and also that the wayside surface along this 3 miles of route length was all “Hard Rock”. Wayside surface occurrence frequencies for each representative route were then calculated as the sum of all the route segment lengths that lay over Map Unit subcomponents which had been assigned the same wayside surface type divided by the total length of the representative route.

6.6.3 Representative Spent Fuel Truck Transportation Routes

Each of the four representative spent fuel truck shipment routes examined originated at a commercial power reactor and terminated at Yucca Mountain, Nevada, the site proposed for the permanent repository for commercial power reactor spent fuel. The four power reactor origins for these routes were chosen because each was close to several other commercial power reactors and/or began in a different region of the United States. Table 7 lists the power plant origin of each route and the principal Interstate Highways that the route follows on its way to Yucca Mountain.

Table 7: Representative Yucca Mountain Route Characteristics

Route Origin	Region	Principal Interstate Highways Traversed
Three Mile Island Nuclear Plant, PA	Northeast	I-80
Brunswick Nuclear Plant, NC	Southeast	I-40
Humboldt Bay Nuclear Plant, CA	Southwest	I-5 and I-15
Trojan Nuclear Plant, OR	Northwest	I-84 and I-15

Routes from these four nuclear power plants to Yucca Mountain were defined by the Oak Ridge National Laboratory (ORNL) WebTRAGIS routing utility [29] as constrained by the applicable government regulations that are incorporated in the utility.

GIS methods of analysis (ARCVIEW [27]) were used to overlay these four representative spent fuel truck cask shipment routes onto the STATSGO digitized map of the continental United States and then to determine the wayside-surface occurrence frequencies (1) for truck accident sites along one of these routes for accidents that occurred during the years 1996 through 2000 and (2) for the wayside-surface lengths along each of these four representative routes. Wayside surface occurrence frequencies were determined for accident sites in order to see whether accident locations were random with respect to site surface characteristics or whether more accidents occurred at locations with hard wayside surfaces (e.g., near hard rock outcrops in mountainous stretches of Interstate Highways).

6.6.4 Comparison of Accident Site and Route Wayside Surface Occurrence Frequencies

The route from the Brunswick Nuclear Plant in North Carolina to Yucca Mountain was selected for comparison of wayside surface hardnesses at accident sites to hardnesses along the entire route. This route was selected because it is a major truck shipment corridor from the east coast to Barstow, CA, that crosses the Appalachian Mountains, the Great Plains, and the Rocky Mountains. Thus, this route encompasses a comprehensive range of geological regions and surface conditions.

Accident locations in the FARS database are specified by “mile-point” to the nearest 0.1 mile, while accident locations are not available in the MCMIS or GES databases. Therefore, FARS heavy truck accident data was used to identify accident locations along the Brunswick Nuclear

Plant to Yucca Mountain transportation route for the years 1996 through 2000. Although the FARS database only contains data for accidents that involve a fatality, the severity spectrum of these accidents should be broad since some accidents that lead to the death of the truck driver are likely to be quite severe compared to truck accidents that only lead to the death of a pedestrian, a motorcyclist, or some other individual much more vulnerable than the truck driver.

GIS methods of analysis, the definitions for “Hard Rock”, “Soft Rock”, and “Rocky Soil” developed above, and the STATSGO database were used to determine (1) the route wayside surfaces along the entire length of the Brunswick Nuclear Plant to Yucca Mountain transportation route, and (2) the surface characteristics of the accident sites for 591 fatal truck accidents that occurred along this route during the years 1996 through 2000. These results were developed for each state along the route. The fractional occurrence of surface types at fatal truck accident sites was calculated by dividing the number of accidents that occurred at “Hard Rock”, “Soft Rock”, and “Rocky Soil” accident sites in each state by the total number of accidents that occurred on the portion of the route that lay within the state. For each Map Unit in each state, the number of accidents that occurred, for example, at “Hard Rock” accident sites, was calculated as the product of the number of accident sites on the portion of the route that lay over the Map Unit and the fraction of the total Map Unit Area occupied by subcomponents with “Hard Rock” wayside surfaces. Similarly, the fractional occurrence (occurrence frequencies) of these three wayside surface types was calculated for each state by summing the route segment lengths that traversed each surface type within the state and dividing the sum by the total route length in the state. These results are presented in Table 8.

Table 8: Surface Occurrence Fractions for Accident Sites and Wayside Surfaces on the Brunswick Nuclear Plant to Yucca Mountain Route

	Accident Fractions			Length Fractions		
State	**Hard Rock**	**Soft Rock**	**Rocky Soil**	**Hard Rock**	**Soft Rock**	**Rocky Soil**
N. Carolina	0.000	0.055	0.000	0.002	0.041	0.000
Tennessee	0.050	0.023	0.000	0.041	0.034	0.000
Arkansas	0.040	0.000	0.000	0.085	0.000	0.000
Oklahoma	0.058	0.029	0.000	0.065	0.043	0.000
Texas	0.000	0.000	0.000	0.006	0.004	0.000
New Mexico	0.200	0.061	0.005	0.233	0.051	0.002
Arizona	0.093	0.000	0.049	0.144	0.041	0.048
California	0.111	0.006	0.001	0.100	0.016	0.002
Entire Route	**0.076**	**0.023**	**0.007**	**0.085**	**0.032**	**0.007**

Table 8 shows that:

- Only 11 percent = 100 × (0.076 + 0.023 + 0.007) of the 591 fatal truck accidents occurred at sites with hard surfaces (i.e., “Hard Rock”, “Soft Rock”, “Rocky Soil”).

- “Hard Rock”, “Soft Rock”, and “Rocky Soil” state accident site occurrence fractions with magnitudes of 0.01 or more generally differ from the corresponding state length fractions by factors of two or less.

- “Hard Rock”, “Soft Rock”, and “Rocky Soil” accident site occurrence fractions for the entire route differ from the length fractions for the entire route by at most 30 percent.

Since these results do not indicate that accidents occur preferentially at locations with hard wayside surfaces and show that wayside surface occurrence frequencies are quite similar to accident site occurrence frequencies, wayside surface occurrence frequencies for the event tree (Figure 2) were calculated using surface hardness data for the entire route lengths of all four routes rather than just for route accident sites.

6.6.5 Route Wayside Surface Occurrence Frequencies

Table 9 presents the occurrence frequencies for route wayside surfaces that were calculated using route length data (not accident site data) for each of the four representative spent fuel truck shipment routes defined in Table 7. For each route, the wayside occurrence frequency values calculated for “Hard Rock”, “Soft Rock”, “Rocky Soil”, and “Water” are presented for the entire route and also for each state traversed by the route. In Table 9, the occurrence frequency values for “Other Soils, Clay, Silt” was calculated as one minus the sum of the occurrence frequencies for “Hard Rock”, “Soft Rock”, “Rocky Soil”, and “Water”. Table 9 also presents the average route wayside surface occurrence frequencies that were calculated for each surface type as distance-weighted sums for all of the values in the table for each surface type using the distance of the route in each state as the weighting factor for that value.

When rounded to three decimal places, the Distance-Weighted Average Values for the route wayside occurrence frequencies for “Hard Rock”, “Soft Rock”, “Rocky Soil”, and “Water”, and for “Other Soils, Clay, Silt” presented in Table 9 become respectively 0.055, 0.043, 0.007, 0.002, and 0.893. Summing the occurrence frequencies for “Soft Rock” and “Rocky Soil” yields 0.050. Since water is a soft, often shallow surface that occurs infrequently, it was combined with “Other Soils, Clay, Silt” in Figure 3. Accordingly, the values for the route wayside occurrence frequencies used in Figure 3 to calculate the probabilities for the sub-branches of the Into Slope, Embankment event tree branch (accident paths 15 through 17) are 0.055 for “Hard Rock”, 0.050 for “Soft Rock, Rocky Soil”, and 0.895 for “Other Soils, Clay, Silt”.

Table 9: Route Wayside Surface Occurrence Frequencies

State Traversed	Surface Type				
	Hard Rock	**Soft Rock**	**Rocky Soil**	**Water**	**Other**
	Three Mile Island. Nuclear Plant, PA, to Yucca Mountain, NV (Primarily on I-80)				
Pennsylvania	0.0064	0.0943	0.0121	0.0023	0.8849
Ohio	0.0014	0.0345	0.0000	0.0000	0.9641
Indiana	0.0000	0.0000	0.0000	0.0000	1.0000
Illinois	0.0150	0.0155	0.0000	0.0013	0.9682
Iowa	0.0010	0.0081	0.0000	0.0006	0.9903
Nebraska	0.0000	0.0168	0.0000	0.0019	0.9813
Wyoming	0.0678	0.1863	0.0066	0.0000	0.7393
Utah	0.0648	0.0489	0.0167	0.0022	0.8674
Arizona	0.0929	0.4680	0.0000	0.0000	0.4391
Nevada	0.0287	0.0046	0.0000	0.0000	0.9667
Route Average*	**0.0251**	**0.0599**	**0.0047**	**0.0010**	**0.9092**
	Brunswick Nuclear Plant, NC, to Yucca Mountain, NV (Primarily on I-40)				
N. Carolina	0.0018	0.0407	0.0000	0.0000	0.9576
Tennessee	0.0414	0.0340	0.0000	0.0057	0.9188
Arkansas	0.0855	0.0000	0.0000	0.0059	0.9086
Oklahoma	0.0649	0.0427	0.0000	0.0043	0.8881
Texas	0.0056	0.0042	0.0000	0.0000	0.9902
New Mexico	0.2329	0.0510	0.0020	0.0007	0.7133
Arizona	0.1436	0.0408	0.0483	0.0000	0.7672
California	0.1001	0.0160	0.0017	0.0000	0.8822
Nevada	0.0306	0.0000	0.0000	0.0000	0.9694
Route Average*	**0.0826**	**0.0306**	**0.0065**	**0.0021**	**0.8782**
	Humboldt Bay Nuclear Plant, CA, to Yucca Mountain, NV (Primarily on I-5 and I-15)				
California	0.0493	0.0554	0.0032	0.0014	0.8907
Nevada	0.0306	0.0000	0.0000	0.0000	0.9694
Route Average*	**0.0468**	**0.0482**	**0.0028**	**0.0012**	**0.9010**
	Trojan Nuclear Plant, OR, to Yucca Mountain, NV (Primarily on I-84 and I-15)				
Washington	0.0157	0.0000	0.0104	0.0260	0.9479
Oregon	0.0921	0.0214	0.0457	0.0166	0.8242
Idaho	0.0651	0.0023	0.0012	0.0005	0.9309
Utah	0.0453	0.0379	0.0110	0.0006	0.9051
Arizona	0.0929	0.4680	0.0000	0.0000	0.4391
Nevada	0.0287	0.0046	0.0000	0.0000	0.9667
Route Average*	**0.0605**	**0.0296**	**0.0171**	**0.0059**	**0.8870**
All States*	**0.0551**	**0.0424**	**0.0072**	**0.0023**	**0.8929**

*Distance-Weighted Average Values

6.6.6 Occurrence Frequencies for Surfaces under Interstate Highway Bridges

Occurrence frequencies for the surfaces under Interstate Highway bridges that might be struck by the spent fuel cask, if an accident on a bridge caused the truck and/or the cask to fall off the bridge, were developed using bridge data for the Trojan Nuclear Plant, OR, to Yucca Mountain, NV, and Three Mile Island, PA, to Yucca Mountain, NV routes. The lengths of Interstate highway bridges that carried the Interstate over a water body, a railway, or another highway were tabulated and the following equations were then used to calculate the fraction of the surfaces under these bridges that were Water, Railbeds or Roadbeds, and ground (either "Hard Rock", or "Soft Rock, Rocky Soil", or "Other Soils, Clay, Silt").

$$L_T = \left[\sum_{i=1}^{N_T} L_i\right] \qquad \text{Equation 7}$$

$$L_{GT} = L_T - N_R L_R - N_H L_H - \sum_{n=1}^{N_W} L_{Wi} \qquad \text{Equation 8}$$

$$f_W = \frac{\sum_{n=1}^{N_W} L_{Wi}}{L_T} \qquad \text{Equation 9}$$

$$f_{R+H} = \frac{N_R L_R + N_H L_H}{L_T} \qquad \text{Equation 10}$$

$$f_G = \frac{L_{GT}}{L_T} \qquad \text{Equation 11}$$

$$f_{HRB} = f_G f_{HR} \qquad \text{Equation 12}$$

$$f_{SRB} = f_G f_{SR} \qquad \text{Equation 13}$$

$$f_{OSB} = f_G f_{OS} \qquad \text{Equation 14}$$

Where:

N_T = total number of bridges on the two representative routes
N_R = number of bridges that cross a rail line
N_H = number of bridges that cross a highway
N_W = number of bridges that cross a navigable waterway
L_i = length of bridge "i"

L_R = average width of a two track rail line
L_H = average width of the highways under route bridges
L_{Wi} = width of the navigable waterway under bridge i
L_{GT} = total length of ground under bridges on the two representative routes
L_T = total length of all of the bridges on the two representative routes
f_W = fraction of total under-bridge length that is navigable water
f_{R+H} = fraction of total under-bridge length that is a Railbed or a Roadbed
f_G = fraction of total under-bridge length that is ground, where ground is either "Hard Rock", or "Soft Rock, Rocky Soil", or "Other Soil, Clay, Silt"
f_{HRB} = fraction of total under-bridge length that is "Hard Rock"
f_{SRB} = fraction of total under-bridge length that is "Soft Rock, Rocky Soil"
f_{OSB} = fraction of total under-bridge length that is "Other Soil, Clay, Silt"
f_{HR} = fraction of route wayside length along the four representative routes that is "Hard Rock" (Taken from Table 9)
f_{SR} = fraction of route wayside length along the four representative routes that is "Soft Rock, Rocky Soil" (Taken from Table 9)
f_{OS} = fraction of route wayside length along the four representative routes that is "Other Soil, Clay, Silt" (Taken from Table 9)

Inspection of this set of equations shows that the occurrence fractions under bridges, f_{HRB}, f_{SRB}, and f_{OSB}, for "Hard Rock", for "Soft Rock, Rocky Soil", and for "Other Soils, Clay, Silt" were calculated assuming that the occurrence under bridges of each of these types of ground is about the same as it is along the sides of the four representative spent fuel truck shipment routes.

Values for the parameters in this equation set, other than f_{HRB}, f_{SRB}, and f_{OSB}, were calculated as follows. The number of bridges, the lengths of these bridges, and the widths of highways under these bridges on the Trojan Nuclear Plant, OR, to Yucca Mountain, NV, and Three Mile Island, PA, to Yucca Mountain, NV routes were taken from the Bridge database [30]. All railways under bridges on these two routes were assumed to have two tracks and the width of a two-track railway was taken to be 6 meters. The widths of highways on the Trojan Nuclear Plant to Yucca Mountain and Three Mile Island to Yucca Mountain routes were respectively assumed to be 6 and 8 meters. Since, for shallow water bodies, the ground under the water body is the impact surface of concern, the under-bridge route length that was classed as water was calculated as the sum of the widths of navigable waterways crossed by the two representative routes, using data taken from the Bridge database [30]. Since some rivers that aren't shallow but are dammed will not be designated as navigable, this approach should have yielded an underestimate of the fraction of under-bridge route length that is deep enough so that the water will be the impact surface of concern. Since water is a soft surface, this underestimate is conservative with regard to estimating spent fuel truck accident risks.

Table 10 presents the parameter values used to calculate the occurrence frequencies of surfaces under bridges for the Trojan Nuclear Plant to Yucca Mountain and the Three Mile Island Nuclear Plant to Yucca Mountain routes, and also the results of the calculations for each of these routes.

Table 10: Under-Bridge Route Length Fractions for Two Representative Routes

Parameter	Route	
	Trojan Nuclear Plant to Yucca Mountain	Three Mile Island Nuclear Plant to Yucca Mountain
	Values of Input Parameters	
N_T	956	2031
N_R	109	207
L_R	6 m	6 m
N_H	609	1097
L_H	8 m	6 m
ΣL_{Wi}	641 m	887 m
L_T	62202 m	108441 m
	Values of Calculated Parameters	
L_{GT}	56035 m	99730
f_R	0.011	0.011
f_H	0.078	0.061
f_{R+H}	0.089	0.072
f_W	0.010	0.0082
f_G	0.901	0.920

Length-weighted summation of the values in this table for f_{R+H}, f_W, and f_G for the two routes, together with calculation of $f_{HRB} = f_{GAv}f_{HR}$, $f_{SRB} = f_{GAv}f_{SR}$, and $f_{OSB} = f_{GAv}f_{OS}$, using values for f_{HR}, f_{SF}, and f_{OS} taken from Table 9, then yielded the following average values for occurrence fractions for under-bridge surfaces:

$f_G = 0.913$, $f_{HRB} = 0.050$, $f_{SRB} = 0.046$, $f_{OSB} = 0.817$, $f_{R+H} = 0.078$, and $f_W = 0.009$.

7.0 New Heavy Truck Accident Event Tree

Placement of the branch-point probability values developed in Section 6.0 on the new heavy truck accident event tree structure presented in Figure 2 and calculation of scenario probabilities yielded the event tree presented in Figure 3. In this figure, the scenario probability values listed in the second-to-the-last column on the figure equal the product of all of the branch point probabilities that lie on that scenario pathway. All of these scenario probabilities are conditional on the occurrence of an accident on an Interstate Highway.

Accident	Type	Object Struck	Speed Distribution	Surface Struck	Probability	Index
Large Truck Accident On Interstate Highway	Collision w non-fixed object 0.820	Train 0.001	Train Grade Crossing Accident Speeds		0.00082	1*
		Gasoline Tanker Truck 0.003			0.00246	2
		Other Vehicles (motorcycles, cars, other trucks) 0.938			0.76916	3
		Other smaller non-fixed objects (e.g., cones, animals, pedestrians) 0.058			0.04756	4
	Collision w fixed object 0.054	Bridge Accident 0.064 → Fall off Bridge 0.02		Hard Rock 0.050	3.46E-06	5**
				Soft Rock, Rocky Soil 0.046	3.18E-06	6*
				Other Soils, Clay, Silt 0.817	5.65E-05	7
				Railbed, Roadbed 0.078	5.39E-06	8
				Water 0.009	6.22E-07	9
		Bridge Accident 0.064 → Strike Bridge Structure 0.98 → Large Column 0.03	Initial Accident Speeds		0.00010	10**
		Bridge Accident 0.064 → Strike Bridge Structure 0.98 → Small Columns, Abutments, Other 0.97	Initial Accident Speeds		0.00329	11*
		Building, Wall 0.010	Initial Accident Speeds		0.00054	12*
		Other fixed objects (trees, signs, barriers, posts, guard rails) 0.636			0.03434	13
		Slide on/into Ground, Culvert, Ditch 0.244			0.01318	14
		Into Slope, Embankment 0.046	Initial Accident Speeds	Hard Rock 0.055	0.00014	15**
				Soft Rock, Rocky Soil 0.050	0.00012	16*
				Other Soil, Clay, Silt 0.895	0.00222	17
	Non-Collision 0.126	Fire/Explosion 0.050			0.00630	18*
		Other Non-Collision (jackknife, rollover, mechanical problems) 0.950			0.11970	19

Figure 3: New truck accident event tree

*Accident scenarios that might lead to cask failure (loss of containment)

**Collision accidents judged to pose significant threats

8.0 Accident Probability Expressions

The probability, P, that a truck carrying a spent fuel cask is involved in an accident so severe that it results in release of radioactive material is the product of the probability per trip that any accident occurs ($P_{accident}$) and the fraction ($F_{severity}$) of all of the accidents that might occur which would lead to releases of radioactive material:

$$P = P_{accident} \times F_{severity} \qquad \text{Equation 15}$$

$$P_{accident} = \sum_{i=1}^{n} L_i R_i \qquad \text{Equation 16}$$

$$F_{severity} = P_{scenario,j} \times P_{speed} \qquad \text{Equation 17}$$

Where:

L_i = the length (km per trip segment) of the ith segment on the shipment route
R_i = the truck accident rate (truck accidents per truck-km) of the ith segment on the shipment route
$F_{severity}$ = the nature of the accident for collision accidents that don't initiate fires
$P_{scenario,j}$ = the probability of collision accident "j" depicted in Figure 3
P_{speed} = the probability that this accident scenario occurs at a particular speed high

P_{speed} is usually calculated as the difference between two values on either the cumulative distribution of truck speeds at accident initiation or the distribution of cask impact speeds onto the ground should the accident cause the truck and cask, or just the cask to fall off of a bridge. Thus,

$$P_{speed} = P_{speed,max} - P_{speed,min} \qquad \text{Equation 18}$$

where $P_{speed,max}$ and $P_{speed,min}$ define the range of accident speeds that can cause release of radioactive material.

For accidents that occur on bridges, the cask impact speed (v_G) onto the ground under the bridge is $v_G = \sqrt{2gh}$ where g is the acceleration due to gravity and h is the height of the bridge. Accordingly, cumulative distributions of initial truck accident speeds and of the heights of bridges on spent fuel shipment routes are needed to develop values for P_{speed}. These cumulative distributions are developed in Section 8.1, Speed Distributions.

When a collision accident initiates a fire,

$$F_{severity,j} = P_{scenario,j} \times P_{speed} \times P_{fire/scenario,j} \times P_{fire\ severity} \qquad \text{Equation 19}$$

Where:

$P_{fire/scenario,j}$ = the chance that accident scenario j initiates a fire
$P_{fire\ severity}$ = the probability that the resulting fire is of a given severity.

If the accident is a fire-only accident, then

$$F_{severity,j} = P_{fire\text{-}only\ accident} \times P_{fire\ severity} \quad \text{Equation 20}$$

Where:

$P_{fire\text{-}only\ accident}$ = the probability of a fire-only accident.

In either case $P_{fire\ severity}$ depends on the size, duration, and average temperature of the fire, and the offset distance between the fire and the spent fuel cask.

The response of a NAC-LWT truck cask to fires has been modeled using the CAFE-P/Thermal code system [31]. These calculations show that, if a significant portion of the cask's surface is not engulfed by the fire's flame envelope, regardless of the fire's duration, convective and radiative heat losses from these un-engulfed surfaces to the atmosphere will limit cask shell and internal temperatures to about 600 C or less [32]. But cask elastomeric seals fail if exposed to temperatures of 400 C for short periods of time and spent fuel rods fail by burst rupture if heated to temperatures ≥ 700 C. Thus, these calculations indicate that, if only partially engulfed by fire, regardless of the duration of the fire, a spent fuel cask most likely can't be heated to temperatures where spent fuel rods fail by burst rupture, although the cask closure may reach temperatures where elastomeric seals will fail by thermal degradation. Therefore,

$$P_{fire\ severity} = P_{colocated} \times P_{optically\ dense} \times P_{temperature} \times P_{duration} \quad \text{Equation 21}$$

Where:

$P_{colocated}$ = the probability that the fire and the cask are co-located,
$P_{optically\ dense}$ = the probability that the fire diameter is just large enough to make the fire's flame envelope optically dense with respect to radiation of heat from the cask through the flame envelope to the atmosphere
$P_{temperature}$ = the probability that the fire fuel burns hot enough to raise the cask to temperatures of concern (e.g., seal failure or rod burst rupture temperatures)
$P_{duration}$ = the probability that the fire burns long enough for these temperatures to be reached.

Data that can be used to estimate values for $P_{colocated}$, $P_{optically\ dense}$, $P_{temperature}$, $P_{duration}$ is presented in Section 8.2.

8.1 Speed Distributions

The Modal Study constructed accident speed distributions for truck accidents that involved:

- a fall from a bridge, or
- a plunge down an embankment
- at a highway/railway grade crossing, or
- on level ground (i.e., not on a steep grade)

For accidents that occurred at highway/railway grade crossings, a distribution of train speeds at the time the train struck the truck was constructed as seen in Figure 4. For highway accidents that didn't lead to a fall from a bridge or a plunge down an embankment (i.e., truck accidents that occurred on level ground or normal highway grades), a distribution of truck speeds at accident initiation was constructed as seen in Figure 5. For accidents that involved a fall from a bridge, a distribution of the heights of the bridges from which the falls occurred was converted to a distribution of truck or cask impact speeds onto the surfaces under the bridge as seen in Figures 6 and 7. For accidents that caused the truck or the cask to plunge down an embankment or a slope, the impact speed distribution was assumed to equal the vector sum of the distribution of initial truck accident speeds and the distribution of impact speeds for accidents that involved falls from bridges.

Calculating a slope speed distribution as a vector sum of an initial speed distribution for truck accidents and a speed distribution derived from a distribution of route bridge heights has two problems. First, it implicitly assumes that the distribution of vertical heights of route wayside slopes is similar to the distribution of route bridge heights, which overestimates slope height occurrence frequencies. Second, it neglects friction between the slope surface and the truck and/or cask, while the truck and/or cask is sliding down the slope or embankment.

The American Association of State, Highway, and Transportation Officials (AASHTO) Interstate Highway construction specifications [33] limit the slope of unbuttressed wayside slopes (a slope not supported by a man-made structure, for example, a retaining wall) to a run over rise ratio of 2/1, which corresponds to a maximum slope relative to the horizontal of 26°. Common highway construction practices use grades of about 6/1 where space and right-of-way allow, and grades steeper than 4/1, which is a typical wayside slope grade, are seeded to minimize erosion [34].

If a large heavy object is placed on a sandy slope, the slope angle that causes the object to begin to slide is greater than the angle required to keep it sliding. Peak friction angles (the angle relative to a horizontal surface required to allow the object to start sliding) on dense, well-graded, coarse sand, slopes usually range from 37° to 60° while ultimate friction angles (the angle required to keep the object sliding) are usually about 30° [35]. Since construction practice and AASHTO specifications mean that most unbuttressed route wayside slopes will have slope angles less than 30° and many wayside slopes will have trees or boulders on them that will prevent an object from sliding down the slope, it seems reasonable to assume that initial truck accident speeds will bound sliding speeds on interstate route wayside slopes. Of course, an accident that leads to a truck sliding down a buttressed slope would be expected to cause the truck to accelerate as it slides. But these accidents should be relatively improbable since slopes that are this steep will almost always have guard rails at the edge of the highway along their extent. For this study, new distributions of initial truck accident speeds and speeds based on route bridge heights were constructed, but no distribution was developed for accidents that lead to the truck sliding down a wayside slope. A speed distribution for highway/railway grade crossings accidents could not be constructed because the Interstate Highway accident data used in this study contained no highway/railway grade crossing accidents. Therefore, for completeness, Figure 4 presents the distribution of train speeds developed for the Modal Study for highway/railway grade crossing accidents [36]. Table 11 presents the data that underlies this plot.

Table 11: Cumulative Distribution of Train Speeds at Highway/Railway Grade Crossing Accidents

Train Speed	Cumulative Fraction	Train Speed	Cumulative Fraction	Train Speed	Cumulative Fraction	Train Speed	Cumulative Fraction
0	0.00000	30	0.74210	62	0.98060	94	0.99960
2	0.06014	34	0.80022	66	0.98717	98	0.99977
6	0.17906	38	0.84814	70	0.99169	102	0.99987
10	0.29398	42	0.88676	74	0.99473	106	0.99993
14	0.40255	46	0.91718	78	0.99672	110	0.99996
18	0.50280	50	0.94062	82	0.99800	114	0.99998
22	0.59331	54	0.95826	86	0.99881	118	0.99999
26	0.67319	58	0.97125	90	0.99930	150	1.00000

The speed distribution presented in Figure 4 was constructed from eight years (1975 - 1982) of accident data [37] using a "maximum entropy" method of estimation [38] to account for uncertainties in the raw data. Use of this estimation method stretches the upper tail of the accident distribution out to accident speeds substantially larger than the largest accident speeds contained in the raw data. This means that high speed accidents are predicted to be more probable by the distribution than by the raw data that underlies the distribution. For example, only 0.02 percent of the highway/railway grade crossing accidents in the raw data occur at speeds greater than 90 mph; the distribution predicts that 0.07 percent of highway/railway grade crossing accidents occur at speeds greater than 90 mph. The distribution predicts that some highway/railway grade crossing accidents may occur at speeds between 110 and 150 mph, even though these speeds would only be attained if a train lost its brakes on an exceedingly long, straight, fairly steep, downhill section of track. Since at these high speeds, derailment would be likely, the occurrence of such accidents borders on the physically impossible. Thus, the long high speed tail of this distribution is misleading. Since a review [39] of rail accident data for the years 1988 through 2001 shows that the highest highway/railway grade crossing accident train speeds are all less than 106 mph, truncation of the Modal Study Highway/Railway Grade Crossing accident train speed distribution presented in Figure 4 at 110 mph might be advisable.

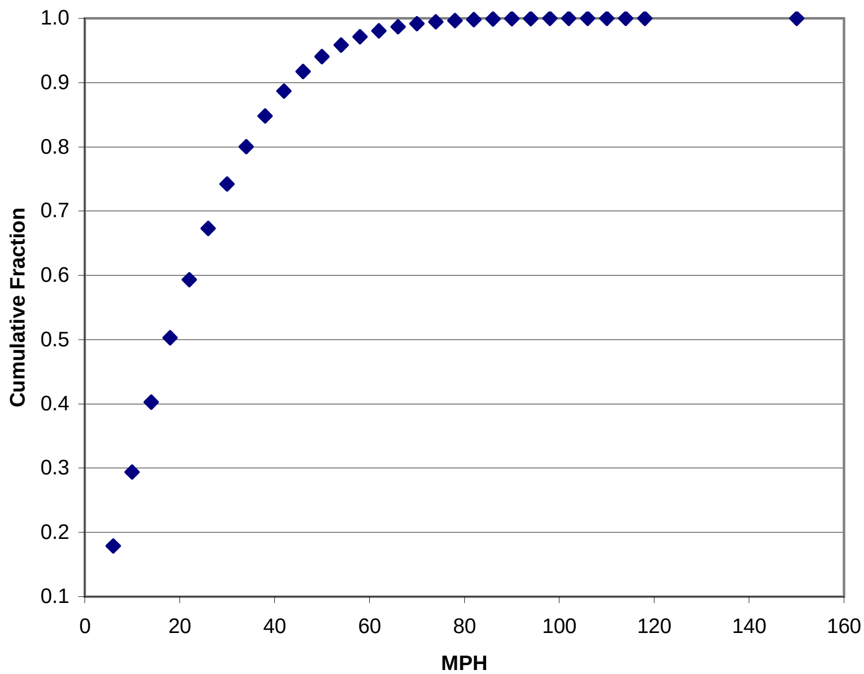

Figure 4: Cumulative Distribution of Highway/Railway Grade Crossing Accident Train Speeds

Cumulative distributions for estimates of truck speeds at the time an accident event were developed using GES data [12] for Medium and Heavy trucks (trucks with Gross Vehicle Weight Ratings > 10,000 lbs) for the years 1996 through 2000 and also FARS data [11] for the same time period. The resulting distributions are plotted in Figure 5. Table 12 presents the data that underlies these plots.

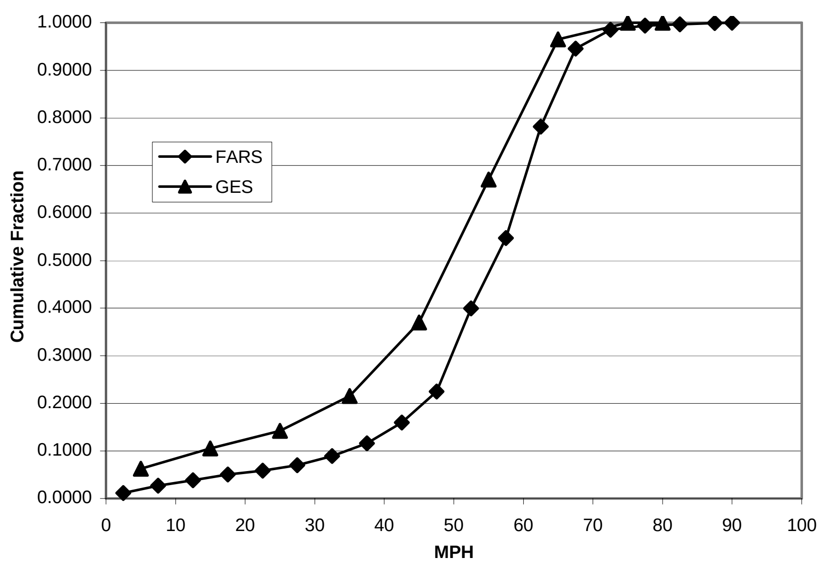

Figure 5: Cumulative Distributions of Truck Speeds at Accident Initiation

Table 12: Cumulative Distributions of Truck Speeds at Accident Initiation

FARS Accident Speeds		GES Accident Speeds	
Accident Speed Range (mph)	Cumulative Fraction	Cumulative Fraction	Accident Speed Range (mph)
0-5	0.0112	0.0628	0-10
5-10	0.0269		
10-15	0.0381	0.1054	10-20
15-20	0.0502		
20-25	0.0583	0.1425	20-30
25-30	0.0695		
30-35	0.0893	0.2157	30-40
35-40	0.1162		
40-45	0.1597	0.3700	40-50
45-50	0.2252		
50-55	0.3997	0.6700	50-60
55-60	0.5473		
60-65	0.7815	0.9652	60-70
65-70	0.9457		
70-75	0.9852	0.9997	70-80
75-80	0.9937		
80-85	0.9969	1.000	80
85-90	0.9996		
90	1.0000		

Figure 5 shows that for any cumulative fraction value, the corresponding FARS estimate of the initial accident speed is higher than the GES estimate which seems reasonable since an average accidents that lead to fatalities might be expected to occur at higher speeds than accidents that do not cause fatalities. Figure 5 also shows that the two distributions show similar results for high-speed accidents. Agreement between FARS and GES data for high-speed accidents is important since these are the accidents most likely to threaten the integrity of a spent nuclear fuel cask.

For accidents where a truck falls from a bridge, the speed of impact (v_G) with the surface under the bridge depends on the height of the bridge. Specifically,

$$v_G = \sqrt{2gh} \qquad \text{Equation 22}$$

Where:

g = the acceleration due to gravity
h = the height of the bridge.

The "National Bridge Inventory Data" CD-ROM, describing highway bridges carrying federally-supported roadways (i.e., highways built or maintained with federal funds), was obtained from the Federal Highway Administration [30]. The database contains a field that tabulates the minimum clearance height under each bridge for bridges that go over railroads, other highways, and gorges, ravines, etc. For bridges over water, this field is empty. Clearance heights for bridges over navigable waterways subject to "navigation control" are tabulated in a separate data field. Because bridges over navigable waterways must have substantial clearance heights to allow ships or barges to pass under them, the heights of these bridges were combined with the heights of bridges that didn't cross a water body, thereby most likely capturing the clearance heights of most high highway bridges. This combined set of bridge height data was then used to construct a distribution of bridge clearance heights for all the bridges on the four representative shipment routes described in Section 6.6.3. This set of bridge heights was then used to derive a distribution of cask impact speeds for falls off of bridges with these heights. These distributions are presented in Figures 6 and 7 and the data underlying these figures are presented in Table 13.

Table 13: Cumulative Distributions of Bridge Heights and Impact Speeds for Falls from Bridges

Cumulative Fraction	Bridge Height (Meters)	Bridges With This Height	Impact Speed (mph)	Cumulative Fraction	Bridge Height (Meters)	Bridges With This Height	Impact Speed (mph)
0.0576	0	215	0.00	0.9995	23	0	47.52
0.0576	1	0	9.91	0.9995	24	0	48.55
0.0576	2	0	14.01	0.9995	25	0	49.55
0.0581	3	2	17.16	0.9995	26	0	50.53
0.0702	4	45	19.82	0.9995	27	0	51.49
0.5885	5	1935	22.16	0.9997	28	1	52.44
0.7841	6	730	24.27	0.9997	29	0	53.36
0.8553	7	266	26.22	0.9997	30	0	54.28
0.9711	8	432	28.03	0.9997	31	0	55.17
0.9858	9	55	29.73	0.9997	32	0	56.06
0.9925	10	25	31.34	0.9997	33	0	56.93
0.9930	11	2	32.87	0.9997	34	0	57.78
0.9946	12	6	34.33	0.9997	35	0	58.63
0.9949	13	1	35.73	0.9997	36	0	59.46
0.9954	14	2	37.08	0.9997	37	0	60.28
0.9954	15	0	38.38	0.9997	38	0	61.09
0.9968	16	5	39.64	0.9997	39	0	61.88
0.9973	17	2	40.86	0.9997	40	0	62.67
0.9984	18	4	42.04	0.9997	41	0	63.45
0.9987	19	1	43.19	0.9997	42	0	64.22
0.9992	20	2	44.32	0.9997	43	0	64.98
0.9995	21	1	45.41	1.0000	44	1	65.73
0.9995	22	0	46.48				

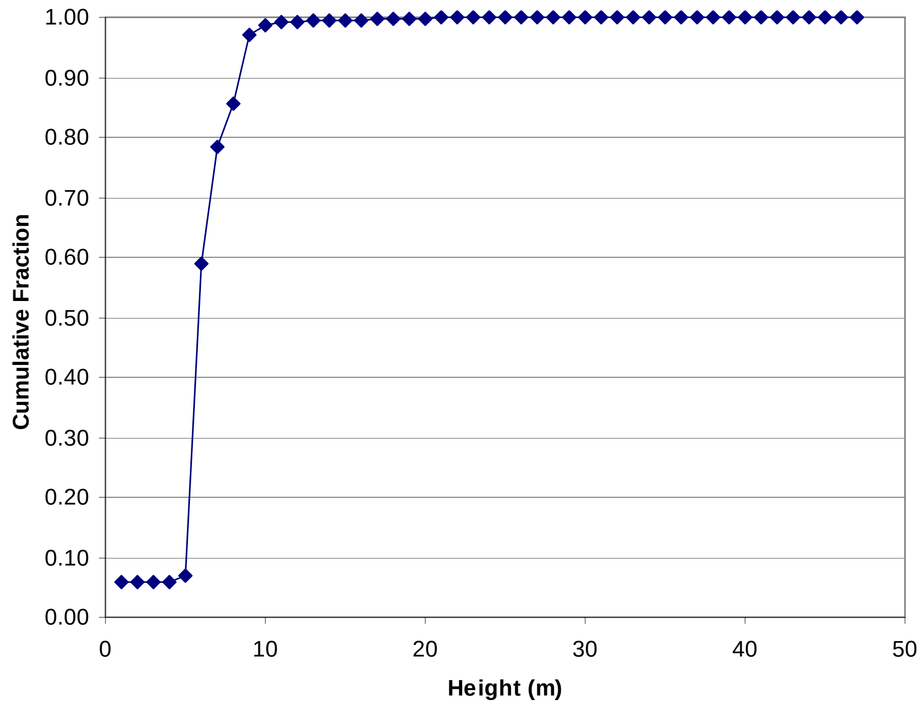

Figure 6: Bridge Height Distribution

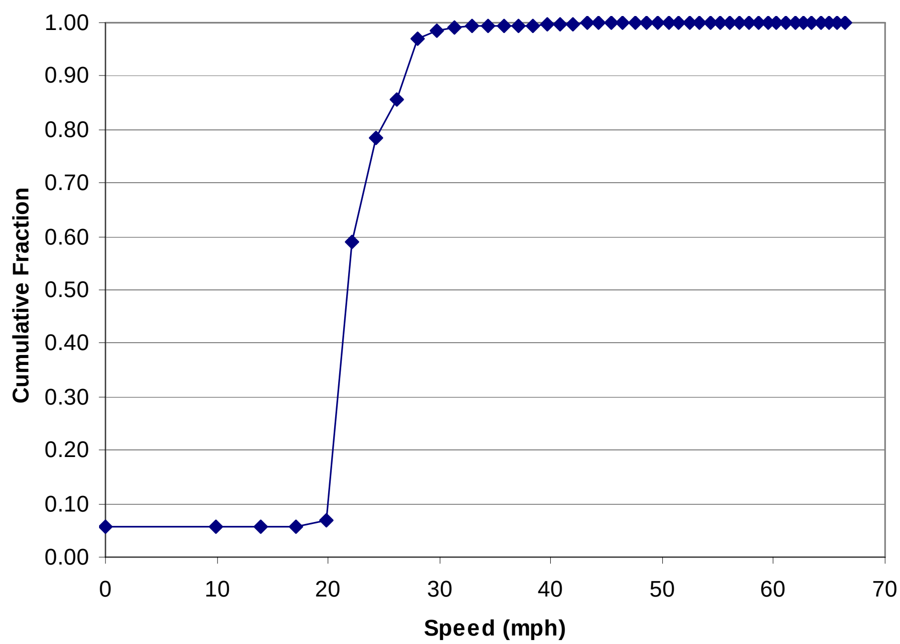

Figure 7: Speed Distribution Based on Bridge Heights

Inspection of Figures 6 and 7 shows that most Interstate highway bridges have clearance heights of about 5 to 10 meters; therefore, should a truck carrying a spent fuel cask be involved in an accident on a bridge that causes the truck with the cask or just the cask to fall off of the bridge, most of the time the cask impact speed will be less than the regulatory certification test impact speed (30 mph onto an unyielding surface).

8.2 Fire Distributions

Statistics for tractor/semi-trailer truck fire accidents have been constructed by Clauss and Blower [40] using data for the years 1992 through 1996 for the Trucks Involved in Fatal Accidents (TIFA) database from the University of Michigan's Transportation Research Institute (UMTRI).

The results developed by Clauss and Blower allow values for $P_{fire/scenario,j}$ and $P_{fire\ severity}$ to be estimated. Table 14 presents the results of this analysis and the following paragraphs describe how the data developed by Clauss and Blower was used to calculate values for $P_{fire/scenario,j}$, $P_{co\text{-}located}$, $P_{optically\ dense}$, $P_{temperature}$, and $P_{duration}$. Smoldering low-temperature fires pose no threat to a spent fuel cask and are unlikely to cause fatalities. Only truck accident fires supported by the combustion of gasoline, diesel fuel, a liquid or gaseous hydrocarbon being transported by a tanker truck are likely to threaten the integrity of a spent fuel cask. Clauss and Blower state, "the fuel source for fires associated with fatal accidents is assumed to be a liquid or gas hydrocarbon" [41]. They also present data [42] that shows the average flame envelope temperatures for almost all liquid or gaseous hydrocarbon fuel fires are greater that 700 C. Therefore, since most truck accident fires will be supported by the burning of the truck's fuel, assuming $P_{temperature}$ = 1.0 for truck accidents is reasonable and somewhat conservative.

Table 14: Values for Fire Probabilities

Most Hazardous Event (MHE)	Total	Fires	$P_{fire/scenario,j}$	$P_{co\text{-}located}$	$P_{optically\ dense}$	$P_{t > 1\ hr}$	$P_{t > 2\ hrs}$
Truck	876	128	0.146	0.40	0.10	0.02	0.0
Car	9846	268	0.027	0.50	0.10	0.0	0.0
Tanker Truck	20	4	0.200	0.40	0.29	0.85	0.33
Train	72	15	0.208	0.42	1.00	0.24	0.02
Hard Fixed Object	228	20	0.088	0.72	0.10	0.0	0.0
Soft Fixed Object	225	17	0.076	0.72	0.10	0.0	0.0
Non-Fixed Object	1135	16	0.014	0.72	0.10	0.0	0.0
Rollover	780	38	0.049	0.66	0.26	0.0	0.0
Fire	188	188	1.000	0.66	0.19	0.0	0.0
Immersion	16	1	0.063	0.66	0.30	0.0	0.0
Unknown	136	52	0.382				
Total	**13522**	**747**	**0.055**				

A hydrocarbon pool fire with a diameter of 23 ft will be optically dense to radiation emitted by a cask centered in this fire because spent fuel truck casks are usually about 17 ft long. Thus,

$P_{optically\ dense} = 1.0 - P_{d < 23\ ft}$ Equation 23

$P_{duration} = 1.0 - P_t$ Equation 24

Where:

$P_{d < 23\ ft}$ = the probability that the fire's diameter is less than 23 ft
P_t = the probability that a fire has a duration ≤ t hrs

Values of P_t are taken from Table 15, and t is some reference fire duration of concern, for example, one hour or two hours, which respectively are the durations [43] of co-located, fully engulfing, optically dense, hydrocarbon pool fires that will heat a spent fuel truck cask to the temperatures at which cask elastomeric seals fail by thermal degradation and spent fuel rods fail by burst rupture.

The TIFA data examined by Clauss and Blower categorizes truck accidents by the Most Hazardous Event (MHE), which may be a collision with another vehicle or an object, or the most hazardous outcome of the accident (e.g., rollover of the truck, initiation of a fire, or immersion in a river or lake). For the years 1992 through 1996, Clauss and Blower tabulated for each MHE the number of truck accidents that fall into each MHE category, the number of accidents in each category that lead to fires, and the fraction of these fires that were co-located with the truck. Clauss and Blower also constructed distributions of fire size and of fire duration.

Because data on fire sizes is almost non-existent, Clauss and Blower developed fire duration distributions for fires of various sizes (e.g., pool diameters of 5, 10, 15, … ft) [44]. Pool fire diameters were assumed to be just large enough for the pool recession rate times its area to equal the spill rate of fuel from the failed truck fuel tank. Insertion of a distribution of fuel tank sizes [45] into the relationship between spill rate and burn rate then produced a distribution of fire durations for pool fires of any specified diameter.

For each MHE, the ratio of the number of accidents that lead to fires and the total number of accidents in this category gives the value of $P_{fire/scenario,j}$ for this accident category, and the fraction of fires that are engulfing fires [46] gives the value of $P_{co\text{-}located}$. These values are presented in Table 14, which shows that only accidents where the struck vehicle is another truck, a tanker truck, or a train lead to fires with durations long enough to cause truck cask seals or the spent fuel rods to fail. Table 14 also shows that the chance that a truck accident initiates a co-located, optically dense, hydrocarbon pool fire that burns long enough to cause cask seal or spent fuel rod failure is quite small. For example from Table 14, the chance that a truck/tanker truck collision leads to a fire-only accident that lasts at least two hours is only about

$$\begin{aligned} P_{fire\ severity} &= P_{fire\text{-}only\ accident} \times P_{co\text{-}located} \times P_{optically\ dense} \times P_{temperature} \times P_{duration} \\ &= (0.200)(0.40)(0.29)(1.0)(0.33) = 7.7\text{x}10^{-3}. \end{aligned}$$

The cumulative fire duration distributions for truck/truck, truck/train, and truck/tanker truck pool fires with diameters of 25 ft or less that were developed by Clauss and Blower are presented in Table 15 and are plotted in Figure 8.

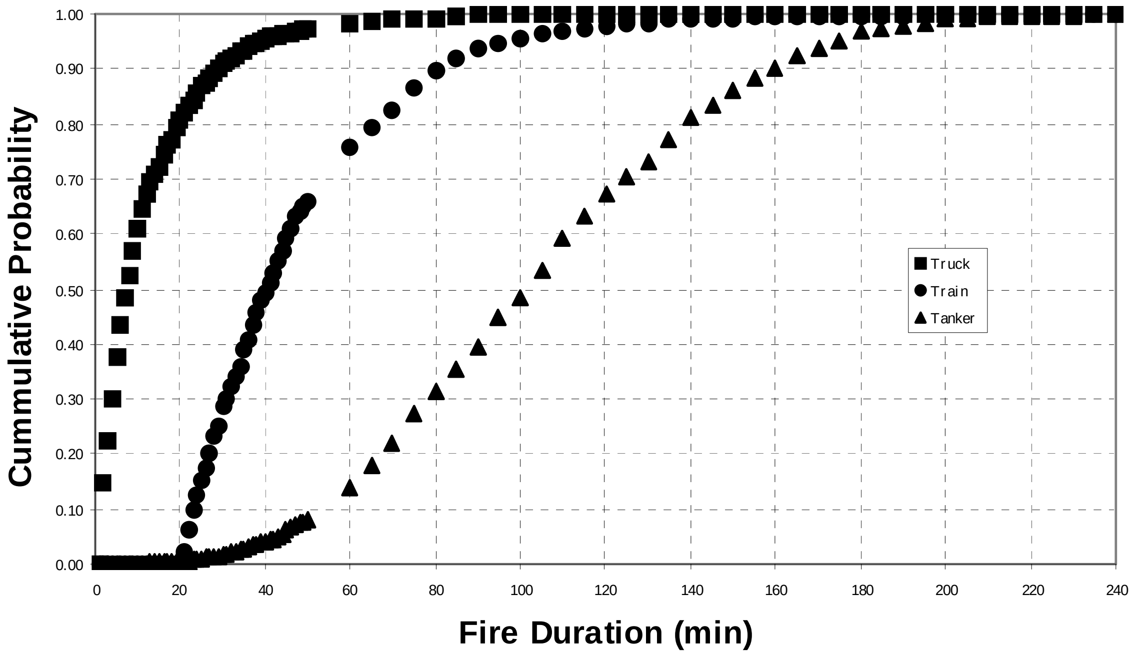

Figure 8: Cumulative Fire Duration Distributions for Truck/Truck, Truck/Train, and Truck/Tanker Truck Fire Accidents

Table 15: Cumulative Probabilities for Fire Durations for 25 Ft Pool Fires for Truck/Truck, Truck/Train, and Truck/Tanker Truck Fire Accidents

Fire Duration (min)	Cumulative Probability			Fire Duration (min)	Cumulative Probability		
	Truck	Train	Tank		Truck	Train	Tank
1.00E+00	4.89E-04	2.44E-05	1.62E-04	4.60E+01	9.66E-01	6.10E-01	6.57E-02
2.00E+00	1.47E-01	4.89E-05	3.23E-04	4.70E+01	9.68E-01	6.31E-01	6.99E-02
3.00E+00	2.23E-01	7.33E-05	4.85E-04	4.80E+01	9.70E-01	6.39E-01	7.40E-02
4.00E+00	3.03E-01	9.78E-05	7.36E-04	4.90E+01	9.71E-01	6.50E-01	7.78E-02
5.00E+00	3.76E-01	1.22E-04	9.97E-04	5.00E+01	9.72E-01	6.60E-01	8.20E-02
6.00E+00	4.35E-01	1.47E-04	1.26E-03	6.00E+01	9.84E-01	7.60E-01	1.38E-01
7.00E+00	4.83E-01	1.71E-04	1.51E-03	6.50E+01	9.87E-01	7.93E-01	1.77E-01
8.00E+00	5.27E-01	1.96E-04	1.65E-03	7.00E+01	9.91E-01	8.24E-01	2.21E-01
9.00E+00	5.69E-01	2.20E-04	1.78E-03	7.50E+01	9.93E-01	8.63E-01	2.72E-01
1.00E+01	6.08E-01	2.44E-04	1.92E-03	8.00E+01	9.93E-01	8.98E-01	3.14E-01
1.10E+01	6.45E-01	2.69E-04	2.06E-03	8.50E+01	9.97E-01	9.20E-01	3.56E-01
1.20E+01	6.71E-01	2.93E-04	2.20E-03	9.00E+01	9.98E-01	9.37E-01	3.96E-01
1.30E+01	6.95E-01	3.18E-04	2.33E-03	9.50E+01	9.98E-01	9.44E-01	4.47E-01
1.40E+01	7.08E-01	3.42E-04	2.47E-03	1.00E+02	9.98E-01	9.54E-01	4.86E-01
1.50E+01	7.23E-01	3.67E-04	3.29E-03	1.05E+02	9.99E-01	9.66E-01	5.36E-01
1.60E+01	7.45E-01	3.91E-04	3.87E-03	1.10E+02	9.99E-01	9.70E-01	5.93E-01
1.70E+01	7.62E-01	4.15E-04	4.35E-03	1.15E+02	9.99E-01	9.72E-01	6.31E-01
1.80E+01	7.73E-01	4.40E-04	4.79E-03	1.20E+02	1.00E+00	9.77E-01	6.71E-01
1.90E+01	7.95E-01	4.64E-04	5.20E-03	1.25E+02	1.00E+00	9.81E-01	7.06E-01
2.00E+01	8.05E-01	4.89E-04	5.62E-03	1.30E+02	1.00E+00	9.84E-01	7.32E-01
2.10E+01	8.19E-01	2.06E-02	6.05E-03	1.35E+02	1.00E+00	9.89E-01	7.73E-01
2.20E+01	8.34E-01	6.45E-02	6.47E-03	1.40E+02	1.00E+00	9.91E-01	8.11E-01
2.30E+01	8.44E-01	9.76E-02	6.83E-03	1.45E+02	1.00E+00	9.92E-01	8.36E-01
2.40E+01	8.58E-01	1.24E-01	7.18E-03	1.50E+02	1.00E+00	9.93E-01	8.61E-01
2.50E+01	8.68E-01	1.50E-01	9.09E-03	1.55E+02	1.00E+00	9.93E-01	8.82E-01
2.60E+01	8.75E-01	1.75E-01	1.26E-02	1.60E+02	1.00E+00	9.95E-01	9.01E-01
2.70E+01	8.83E-01	2.01E-01	1.37E-02	1.65E+02	1.00E+00	9.96E-01	9.23E-01
2.80E+01	8.94E-01	2.32E-01	1.43E-02	1.70E+02	1.00E+00	9.97E-01	9.36E-01
2.90E+01	9.01E-01	2.53E-01	1.49E-02	1.75E+02	1.00E+00	9.98E-01	9.50E-01
3.00E+01	9.10E-01	2.87E-01	1.71E-02	1.80E+02	1.00E+00	9.98E-01	9.68E-01
3.10E+01	9.15E-01	3.03E-01	1.81E-02	1.85E+02	1.00E+00	9.98E-01	9.71E-01
3.20E+01	9.18E-01	3.22E-01	2.08E-02	1.90E+02	1.00E+00	9.98E-01	9.75E-01
3.30E+01	9.26E-01	3.39E-01	2.39E-02	1.95E+02	1.00E+00	9.98E-01	9.83E-01
3.40E+01	9.31E-01	3.57E-01	2.63E-02	2.00E+02	1.00E+00	9.98E-01	9.89E-01
3.50E+01	9.33E-01	3.92E-01	2.87E-02	2.05E+02	1.00E+00	9.98E-01	9.93E-01
3.60E+01	9.41E-01	4.09E-01	3.00E-02	2.10E+02	1.00E+00	9.98E-01	9.93E-01
3.70E+01	9.45E-01	4.36E-01	3.40E-02	2.15E+02	1.00E+00	9.98E-01	9.95E-01
3.80E+01	9.47E-01	4.57E-01	3.78E-02	2.20E+02	1.00E+00	9.98E-01	9.96E-01
3.90E+01	9.48E-01	4.80E-01	3.89E-02	2.25E+02	1.00E+00	9.98E-01	9.97E-01
4.00E+01	9.54E-01	4.95E-01	4.01E-02	2.30E+02	1.00E+00	9.98E-01	9.98E-01
4.10E+01	9.59E-01	5.09E-01	4.26E-02	2.35E+02	1.00E+00	9.98E-01	9.99E-01
4.20E+01	9.60E-01	5.29E-01	4.52E-02	2.40E+02	1.00E+00	9.98E-01	1.00E+00
4.30E+01	9.61E-01	5.53E-01	5.09E-02	4.60E+01	9.66E-01	6.10E-01	6.57E-02
4.40E+01	9.63E-01	5.68E-01	5.32E-02	4.70E+01	9.68E-01	6.31E-01	6.99E-02
4.50E+01	9.65E-01	5.92E-01	6.11E-02				

9.0 Comparison with Modal Study Results

It is intersting to compare Modal Study truck accident statistics to truck accident statistics developed using recent GES data [12]. Because the Modal Study truck accident event tree was constructed using data categories derived from mixed data sources (OMC data and California DOT data) [47], the branch-points on the Modal Study tree do not correspond exactly with categories of accidents tabulated in the GES database. In order to identify changes in truck crash statistics (differences between the 1973 through 1983 data that underlies the Modal Study event tree and the 1996 through 2000 GES data used in this study), the major branch points in the Modal Study event tree were aggregated and compared to corresponding aggregations of GES crash category data. This comparison is presented in Table 16.

Table 16: Comparison of Branch-Point Fractions

Modal Study Event Tree	Fraction	GES Database	Fraction*
Collision	**0.74**	**Collision**	**0.86 ± 0.013**
Non-fixed object	0.88	Object Not Fixed	0.96 ± 0.006
Soft objects	0.05	Pedestrian, Pedal cyclist, Animal, Other Non-Motorist	0.02 ± 0.01
Automobile, Truck, Bus, Motorcycle,	0.88	Motor Vehicle. In Trans-port, Parked Motor Vehicle	0.94 ± 0.02
Train	0.01	Railway Train	0.0
Other	0.06	Other Object Not Fixed, Other – No Details	0.04 ± 0.01
On road fixed object	0.12	(On road) Fixed Object	0.04 ± 0.006
Bridge railing, Column, Abutment	0.06	Bridge Structure (Pier, Abutment, Parapet End, Rail)	0.09 ± 0.09
Concrete Object, Bottom Structure, Wall Barrier, Wall, Post	0.46	Guard Rail, Concrete Barrier, Other Longitudinal Barrier,	0.49 ± 0.07
Signs, Cushions	0.06	Post, Sign/Utility Post, Pole, Impact Attenuator or Crash Cushion	0.17 ± 0.06
Curb, Culvert	0.42	Culvert or Ditch, Curb	0.25 ± 0.13
Non-collision	**0.26**	**Non-collision**	**0.14 ± 0.013**
Off Road	0.35	(Off Road)	0.12 ± 0.04
Into Slope	0.28	Embankment, Wall, Building	0.21 ± 0.20
Over Embankment	0.26	Ground	0.17 ± 0.24
Trees	0.10	Tree	0.29 ± 0.24
Other	0.36	Misc.	0.33 ± 0.25
Impact Roadbed	0.53	(Impact Roadbed)	0.38 ± 0.08
Overturn	0.60	Rollover	0.70 ± 0.08
Jackknife	0.40	Jackknife	0.30 ± 0.08
Other involving mechanical loading	0.08	Other Non-Collision, Thrown or Falling Object, No Details	0.46 ± 0.11
Fire only	0.04	Fire/Explosion	0.04 ± 0.03

* GES fraction values are the averages ± the standard deviation of the fractions calculated for each of the five years 1996 through 2000.

The GES fraction values in Table 16 were calculated as averages of the fractions calculated for each of the five years 1996 through 2000. Accordingly, for each GES fraction value, a standard deviation was also calculated. Table 16 shows that five Modal Study fractions have values that do not lie within three standard deviations of the value calculated using recent GES accident data. The GES results show that collisions of any type (GES = 0.86; Modal Study = 0.74) and collisions with Non-Fixed Objects (GES = 0.96; Modal Study = 0.88) are now somewhat more probable, while collisions with Fixed Objects (GES = 0.04; Modal Study = 0.12) are now somewhat less probable than was predicted by the Modal Study. Conversely, non-collision accidents (GES = 0.14; Modal Study = 0.26) are now about half as probable, mainly because off-road non-collision accidents are now much less likely to occur (GES = 0.12; Modal Study = 0.35). Although these differences are statistically significant, the Modal Study and GES fraction values in Table 16 are not so different as to suggest that the nature of truck accidents has changed drastically during the last two decades.

Comparison of Figure 1, the Modal Study event tree, to Figure 3, the new event tree, shows that the frequencies of occurrence for several important accident scenarios have changed significantly. Table 17 provides a summary of the most significant scenario branch-points from both event trees to facilitate this comparison.

Table 17: Summary of End-Point Fractions for Significant Scenarios

Object Struck	Surface Struck	Modal Study (MS)	This Study (TS)	TS/MS
Train		$7.70x10^{-3}$	$8.20x10^{-4}$	0.11
Bridge	Hard Rock	$1.00x10^{-6}$	$3.46x10^{-6}$	3.46
	Soft Rock/Rocky Soil	$6.00x10^{-6}$	$3.18x10^{-6}$	0.53
Large Column		$6.20x10^{-5}$	$1.00x10^{-4}$	1.61
Small Column, Abutment		$2.99x10^{-4}$	$3.29x10^{-3}$	11.00
Building, Wall		$8.50x10^{-4}$	$5.90x10^{-4}$	0.69
Slope, Embankment	Hard Rock	$4.67x10^{-4}$	$1.40x10^{-4}$	0.30
	Soft Rock/Rocky Soil	$2.96x10^{-3}$	$1.20x10^{-4}$	0.04
Fire/Explosion		$9.71x10^{-3}$	$6.30x10^{-3}$	0.65

Table 17 shows that this study finds impacts with small columns and abutments to be about 11 times more probable than was found by the Modal Study. Although this is a large increase, it poses little significance for truck accident risks since small columns and abutments are soft targets for a spent fuel truck cask. Similarly, the much smaller chance that a collision with a slope or embankment will involve "Soft Rock" or "Rocky Soil" is also of little significance as these surface layers are also relatively soft compared to a spent fuel truck cask.

The five years of GES data examined for this report contain no accidents where a truck struck or was struck by a train; this is most likely due to the very limited occurrence of railroad grade crossings on Interstate Highways. Consequently, this report estimated the chance of a truck/train collision to be:

$$8.2x10^{-4} = P_{collision\ w\ non\text{-}fixed\ object} \times P_{train} = (0.82)(0.001)$$

The Modal Study estimated the chance of a truck/train collision to be:

$$7.7x10^{-3} = P_{collision} \times P_{non\text{-}fixed\ object} \times P_{train} = (0.7412)(0.8805)(0.0118)$$

But truck/train collisions are not likely to compromise the integrity of a spent fuel truck cask (i.e. if the truck hits the train, both the truck cab and the cask's impact limiter protect the cask; and if the train hits the truck, the cask is still unlikely to be severely damaged). This is true because a locomotive/cask impact test showed that the "hard" component of the locomotive, the locomotive's frame or sill, will impact and then slide under the lower edge of the cask [48]. Thus, the much lower estimate for truck/train collision frequency developed by this study is expected to be unimportant, since this accident if it were to occur would not be expected to lead to cask failure.

On the Modal Study tree, Figure 1, the chance of a truck having an accident that causes the truck to fall off of a bridge is:

$$5.1x10^{-3} = P_{collision} \times P_{on\ road\ fixed\ object} \times P_{bridge\ railing} = (0.7412)(0.1195)(0.0577)$$

On the new event tree, Figure 2, this chance is:

$$6.9x10^{-5} = P_{collision\ w\ fixed\ object} \times P_{bridge\ accident} \times P_{fall\ off\ bridge} = (0.054)(0.064)(0.02)$$

Thus, the Modal Study estimate for the chance that a truck falls off of a bridge is 74 times greater than the estimate developed by this study, most likely because the Modal Study appears to have assumed that whenever a truck strikes a bridge railing, the truck falls off of the bridge, while this analysis finds that only 2 bridge accidents in 100 result in a fall from the bridge. Were this factor of 0.02 applied to the Modal Study estimate of the fraction of accidents that lead to a collision of a truck with a bridge railing, then the Modal Study estimate of the probability of a fall from a bridge would become:

$$1.0x10^{-4} = P_{collision} \times P_{on\ road\ fixed\ object} \times P_{bridge\ railing} \times P_{fall\ off\ bridge} = (0.7412)(0.1195)(0.0577)(0.02)$$

This result agrees reasonably well with the value of $0.69x10^{-4}$ developed by this study.

Although the analysis presented in Section 6.4 finds that only 2 bridge accidents in 100 lead to a fall from a bridge, the chance that an accident that occurs on a bridge leads to a fall off the bridge onto hard rock under the bridge is found to be:

$$3.46x10^{-6} = P_{collision\ w\ fixed\ object} \times P_{bridge\ accident} \times P_{fall\ off\ bridge} \times P_{Hard\ Rock}$$
$$= (0.054)(0.064)(0.02)(0.050)$$

This result is about a factor of three larger than the Modal Study result:

$$1.02 \times 10^{-6} = P_{collision} \times P_{on\ road\ fixed\ object} \times P_{bridge\ railing} \times P_{Hard\ Rock}$$
$$= (0.7412)(0.1195)(0.0577)(0.000199)$$

The new result is larger than the Modal Study result because the new estimate of the occurrence fraction for Hard Rock under bridges, 0.050, is 251 times larger than the Modal Study estimate of 0.000199 for this fraction. The Modal Study survey of surfaces under bridges simply tallied the principal feature that the bridge was crossing over (e.g., a highway, a railroad track, a stream) without accounting for the amount of ground that was under the length of the bridge on either side of the principal feature. In contrast, the present study considered all of the surfaces under bridges, including the ground on either side of the principal feature, and assumed that the occurrence of ground types (“Hard Rock”, “Soft Rock”, “Rocky Soil”, “Other Soil, Clay, Silt”) under bridges was the same as it was for route wayside surfaces. Therefore, as Table 18 shows, this study finds that rock layers and soil occur under bridges much more often than was found by the Modal Study.

Table 18: Occurrence Fractions for Ground Types Under Bridges

Ground Types	Modal Study (MS)	This Study (TS)	Ratio (TS/MS)
Hard Rock	2.0×10^{-4}	5.0×10^{-2}	251
Soft Rock/Rocky Soil	1.3×10^{-3}	4.6×10^{-2}	36
Other Soils/Clay/Silt	1.5×10^{-2}	8.2×10^{-1}	52

Although impact with hard rock after a fall from a bridge is estimated by this study to occur about three times more often than was estimated by the Modal Study, this increase poses little risk since, as Figure 7 shows, almost all of these impacts will occur at speeds below 30 mph and thus will not lead to cask failure.

10.0 Conclusions

The probabilities of severe accidents during the transport of spent nuclear fuel by truck have not been found to be significantly greater than those estimated in the Modal Study. While some branch-point fractions and scenario probabilities on the reconstructed truck accident event tree (Figure 3) differ from corresponding fractions and scenario probabilities on the Modal Study event tree (Figure 1), none of the differences are expected to significantly alter the risks posed by spent fuel truck cask accidents. Truck/train collisions are estimated by this study to be about 100 times less probable than was estimated by the Modal Study. However, this large decrease will have little effect on truck spent fuel cask transportation risks since truck/train collisions are not likely to cause cask failure. Accidents that lead to cask collisions with large columns and hard rock slopes or embankments are respectively estimated to be somewhat more likely (70% increase) and about as likely as was estimated by the Modal Study. Finally, both studies find the chance of fire-only accidents to be about the same. Thus, both studies estimate similar probabilities for the few accident scenarios that might cause cask failure.

11.0 References

[1] L. E. Fischer, et al., "Shipping Container Response to Severe Highway and Railway Accident Conditions," NUREG/CR-4829, Lawrence Livermore National Laboratory, Livermore, CA, February 1987, Figure 2-3, p. 2-12.

[2] J. L. Sprung et al., "Reexamination of Spent Fuel Shipment Risk Estimates," NUREG/CR-6672, U.S. Nuclear Regulatory Commission, Washington, DC, March 2000, Figure 7.3, p. 7-10.

[3] J. L. Sprung et al., "Spent Nuclear Fuel Transportation Package Performance Study Issues Report," NUREG/CR-6768, U.S. Nuclear Regulatory Commission, Washington, DC, June 2002.

[4] NAC International, *Safety Analysis Report for the NAC Legal Weight Truck Cask*, Revision 27, Docket No. 9225, T-88004, June 1999.

[5] General Atomics, *GA-4 Legal Weight Truck Spent Fuel Shipping Cask Safety Analysis Report for Packaging (SARP*), Revision G, COC 9226, General Atomics Report No. 910469/G, General Atomics, San Diego, CA, 1998 (available from NRC document room).

[6] Ref. 2, Table 4.1, p. 4-2.

[7] Ref. 2, Table 4.2, p. 4-3.

[8] US Code of Federal Regulations, 10 CFR 71, paragraph 73c.

[9] Ref. 2, pps. 5-13, 5-14, and 7-19.

[10] Personal communication, R. Kalan, Sandia National Laboratories, July 2003.

[11] http://www-fars.nhtsa.dot.gov/.

[12] http://www-nrd.nhtsa.dot.gov/departments/nrd-30/ncsa/ges.html.

[13] http://www.fmcsa.dot.gov/factsfigs/mcmis/mcmiscatalog.htm.

[14] http://ai.volpe.dot.gov/CrashProfile/dataqualitybystate.asp.

[15] http://www.umtri.umich.edu/.

[16] U.S. Census Bureau, "United States 1997 Economic Census, Vehicle Inventory and Use Survey," EC97TV-US, U.S. Department of Commerce, Economics and Statistics Administration, October 1999, Table 2a, p. 9.

[17] "National Transportation Statistics 2000," TS01-01, Bureau of Transportation Statistics, U.S. Department of Transportation, April 2001, Table 1-29, p. 45.

[18] Street Atlas 4.0, DeLorme, Yarmouth, ME, 1996.

[19] I. G. Waddoups, "Air Drop Test of Shielded Radioactive Material Containers," SAND75-0276, Sandia National Laboratories, Albuquerque NM 87185, 1975.

[20] Ammerman, D. J., "A Method for Comparing Impacts with Real Targets to Impacts onto the IAEA Unyielding Target", Proceedings of PATRAM 92, Yokohama, Japan. (1992).

[21] Ammerman, D. J., "A Method for Relating Impacts with Yielding and Unyielding Targets", Proceedings of the High Level Waste Management Conference, Tucson, AZ. (1992).

[22] L. J. Bonzon and J. T. Schamaun, "Container Damage Correlation with Impact Velocity and Target Hardness," IAEA-SR-10/21, Transport Packaging for Radioactive Materials, IAEA, Vienna, Austria, 1976.

[23] A., Gonzales, "Target Effects on Package Response: An Experimental and Analytical Evaluation," SAND86-2275, Sandia National Laboratories, Albuquerque NM 87185, 1987.

[24] Ref. 2, p. 5-8.

[25] B. M. Das, "Principals of Foundation Engineering, 2nd Edition, PWS-Kent, Boston MA, 1990, pps. 7-13.
[26] R. E. Goodman, "Introduction to Rock Mechanics," John Wiley and Sons, New York NY, 1980, p. 31.
[27] http://www.ftw.nrcs.usda.gov/stat_data.html
[28] Environmental Systems Research Institute Inc., 380 New York Street, Redlands, CA, 92373-8100.
[29] http://apps.ntp.doe.gov/tragis/tragis.htm.
[30] National Bridge Inventory Data (CD-ROM), U.S. Dept. of Transportation, Federal Highway Admin., Office of Bridge Technology, December 2000.
[31] C. Lopez, et al., "Development and Use of the CAFE-3D Code for Analysis of Radioactive Material Packages in Fire Environments", Proc. of the INMM 44th Annual Meeting, Phoenix, Arizona, July 2003.
[32] Personal communication, C. Lopez, SNL.
[33] Standing Committee on Highways, AASHTO Highway Subcommittee on Design, Technical Committee on Geometric Design, "A policy on Design Standards Interstate System," American Association of State Highway and Transportation Officials, Washington DC, January 2005.
[34] Personal communication, M Plesh, NM State Highway Department, 7 July 2003.
[35] T. W. Lambe, "Soil Testing for Engineers," John, Wiley & Sons, New York, 1951, p.94.
[36] Ref. 1, Distribution V4, Table 5.1, p. 5-8.
[37] Ref. 1, Appendix C, Table C.5, p. C-8.
[38] Ref. 1, Appendix G, p. G-1.
[39] Personal communication, S. Chen, DOT Volpe Research Center, Boston MA, September 2001.
[40] D. B. Clauss and D. F. Blower, "A Statistical Description of the Types and Severities of Accidents Involving Tractor Semi-Trailers, Updated Results for 1992-1996," SAND99-2512, Sandia National Laboratories, Albuquerque NM 87185, 1999.
[41] Ref. 40, p. 63.
[42] Ref. 40, Figure 9-5, p. 64.
[43] Ref. 2, Table 6.5, p. 6-7.
[44] Ref. 40, p. 73.
[45] Ref. 40, p. 65.
[46] Ref. 40, Table 9-2, p 65.
[47] See references 18 through 38 in Section 2 of the Modal Study (Ref. 1 in this list of references).
[48] M. Huerta and H. R. Yoshimura, "A Study and Full-Scale Test of a High-Velocity Grade-Crossing Simulated Accident of a Locomotive and a Nuclear-Spent-Fuel Shipping Cask," SAND79-2291, Sandia National Laboratories, Albuquerque NM 87185, Feb. 1983.