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Protective Systems for Spills of Hazardous Materials,

Volume II: Guidelines

Research and Development
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FOREWORD

The highway system may be a source of a wide variety of pollutants to nearby surface and groundwater. The effects of highways on water resources can have an important role in the planning, design, construction, and operation of a transportation system. The Federal Highway Administration and State highway agencies have approached the problem in a multi-phase research effort including studies to:

Phase 1 - Identify and quantify the constituents of highway runoff.
Phase 2 - Identify the sources and migration paths of these pollutants from the highways to the receiving waters.
Phase 3 - Analyze the effects of these pollutants in the receiving waters.
Phase 4 - Develop the necessary abatement/treatment methodology for objectionable constituents.

This investigation was part of the Phase 4 effort. The emphasis is on evaluating the risks, preemptive preventive measures, and toxic material releases from accidents. Typically, the spill contaminants are not the usual constituents of highway runoff. They can occur nonpredictably for short periods and can give very high local impacts.

The final report of this investigation has two volumes: FHWA-RD-96-097 Volume I: Final Report and FHWA-RD-96-098 Volume II: Guidelines.

These publications will be of interest to engineers involved in highway water quality impacts to surface and groundwater and to highway safety specialists. Copies of these publications are being distributed to the Federal Highway Administration regional and division offices and to each State highway agency. Additional copies may be obtained from the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, Virginia 22161.

Charles J. Nemmers, P.E.
Director, Office of Engineering R&D

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16. Abstract

This investigation addressed the identification of potential risks from highway transportation of hazardous materials that would result in severe permanent, irreparable or catastrophic consequences, and the identification of practical and implementable physical protective systems to reduce accident incidents and/or mitigate consequences. The primary concern was to reduce or prevent contamination of surface or ground water resources from flows or other movements of materials from accidental spills of hazardous materials. The hazardous spill substances are likely to be directly toxic or indirectly result in reduced quality of receiving waters.

The results of this study are presented in two reports which are:

FHWA-RD-96-097, Protective Systems for Spills of Hazardous Materials, Volume I: Final Report

FHWA-RD-96-098, Protective Systems for Spills of Hazardous Materials, Volume II: Guidelines

This report presents information on a number of protective systems that could be considered for a particular extreme-risk situation. It does not attempt to make the decision to use or not to use these protective systems. It is not a design manual. The decision and design details remain at the discretion of the user.

Volume I (FHWA-RD-96-097) developed a methodology using a State's panel to identify 11 generalized, ranked extreme risk scenarios and identified protective systems for each. The report concludes that few physical protective systems are available to reduce risk associated with highway transportation of hazardous materials.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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I. BACKGROUND

A. Introduction

This informational guide presents ideas to State planners and designers for practical, feasible, implementable protective systems to reduce the risk of hazardous materials (hazmat) incidents or to mitigate the consequences of hazardous materials spilled within the highway system. The emphasis of the guide is to provide ideas or methods to mitigate or reduce the impact caused by accidental spills of hazardous materials on the highway system by incorporating protective systems into new or reconstructed highway systems.

As used in this guide, a protective system is defined as a physical system; i.e., one that can be constructed, as opposed to regulatory functions. Protective systems should always be considered where appropriate on new construction and reconstruction and at high-risk locations on existing highways. The main objectives of the guide will be to suggest procedures for determining where protective systems should be considered by a suggested risk analysis procedure and what types might be considered.

This guide is not a design manual. It will not cover the nearly infinite number of possible scenarios that States might encounter, nor will it give answers to site-specific or State-specific scenarios. However, it will give enough information to alert the State designer/planner or administrator to situations where there is high risk of a catastrophic occurrence and to assist in the process of determining whether a protective system would be appropriate.

No attempt is made to define "high," as in high-risk. The author cannot emphasize strongly enough that this decision must be made by the various State administrators themselves. There is a great need to study the question, "What is an acceptable level of risk for transportation of hazardous materials on highway systems?" There are no easy answers to this question.

This guide will present a suggested risk model that States can use to define and identify, or flag, potentially high-risk situations and to determine if the system should be designed and implemented. Appropriate types of protective systems that might be used to reduce that risk are presented for various generalized scenarios.

B. Philosophy and Summary of the Guidelines

It should be clear to all that, in this age of modern technology, almost any technological system is feasible and implementable given unlimited resources. The "practicability" of a protective system involves a cost-benefit analysis that includes management decisions by States in regard to the value of a specific reduced risk value or percent reduction. These are not easy decisions, and this guide presents no answers because the decision rests with the State. There is no good data available on how much risk reduction can be achieved with a particular system. Protective systems are a new concept, and there is insufficient history of their effect on accidents and/or spill mitigation. Until such a history is developed over future years, one can only rely on judgment.

Currently, only a few protective systems appear to have clear cut merit in reducing risk of hazardous materials (hazmat) spills and/or mitigating consequences. The most promising, and most applicable to many high-risk situations are in two general categories: (1) high-strength rail to keep hazmat vehicles within the highway system in the event of an accident and (2) closed drainage systems to contain or control spilled material that may result from an accident. These and others should not be overlooked, as preventing one catastrophic occurrence where hundreds of lives could be lost is worth considerable effort. The primary goal of this guide is to ensure that high-risk situations with catastrophic potential are not overlooked and at least considered in the project planning stage. Guidelines on when to consider the use of protective systems are presented in chapter II.

A suggested procedure for determining risk is set forth in chapter III of this manual. This chapter is a guide to risk analysis procedures and associated data needs and will provide a framework for analysis. The ideal approach would be to be able to determine the absolute risk of every highway segment, ramp, bridge, curve, straight section, etc., with and without various protective systems.

Unfortunately, good data is not available. However, the guide discusses the fundamental aspects and procedures of risk assessment and data needs. It will be a primer on practical risk assessment. It advocates using the same risk analysis procedures that are the basis of the Federal Highway Administration (FHWA) Routing Guide.[1] (State personnel should become familiar with the routing guide.) It includes recommendations from a recent

FHWA report on revising procedures in the current routing guide.[2] When better data is available, it can be plugged into the procedures and enhance their value. Traffic and accident data normally collected for planning and other purposes are generally not sufficient for good risk analysis. States should consider altering their traffic data collection systems to make the data bases usable for good risk assessment.

Although the model suggested will have default values, the States should, ideally, develop their own default values or provide their own site-specific data for the model results to be really meaningful in a particular site-specific, high-risk area. Further, it must be emphasized here again that it is up to a State's appropriate decisionmaker(s) to define "high-risk." What level of risk is acceptable, and what level justifies the cost of a protective system? These are tough questions. The guide will provide a framework to develop a risk "value," but it cannot answer the question of whether the value is acceptable or whether the cost of a protective system is justified.

Finally, it must be made clear that this informational guide will present only ideas and examples to fit selected situations from each scenario. It is an extension of two unpublished interim reports from this project covering development of scenarios, prioritization of scenarios, and a Volume I: Final Report giving more detailed information on all phases of the study.[3]

The final chapter, chapter IV, sets forth information on automatic hazmat detection to give administrators, planners, or engineers ideas on what might be adapted to high-risk highway locations where automatic detection and/or communication systems might be warranted. It is emphasized that these detection/communication systems are not available for off-the-shelf use in highway situations. Research and development will be necessary. However, this is a new field--a new concept--and all such systems generally start with a need and an idea; to provide a start is the intent of the chapters on automatic detection systems.

II. WHEN TO CONSIDER PROTECTIVE SYSTEMS

A. Scenario Development and Prioritization

1. Background

One of two key tasks leading to this manual was the development and ranking of a set of extreme-risk (catastrophic) scenarios. The second key task was the development of protective systems presented in the next section of this chapter. An advisory panel of contacts from interested States was formed to assist in the tasks.

All 50 States were advised of the research and given the opportunity to participate by naming an appropriate contact. Eventually 28 States expressed interest in the project and named contacts. One of the State contacts never participated; thus, 27 States were represented on the project advisory panel.

Using a States' panel assured the scenarios developed would represent matters of real concern to the States. Biases are inevitable due to the varied backgrounds of the panel members and the varied experience of the individual States with hazmat flows. However, because the research was to address a cross-section of situations as the States perceived the problem, it was appropriate to develop the scenarios with whatever inherent biases exist in the real world of varied State concerns. No two States are likely to have the same concerns, and no two States would be likely to rank a set of catastrophic scenarios exactly the same, nor even agree on the same set. The fact that a definite consensus was arrived at by the panel was in itself a major accomplishment.

2. Prioritization of scenarios

Through 7 rounds of mailed questionnaires to the advisory panel, the list of 11 scenarios on the following page, table 1, was developed. The final round asked for approval of this list. Although some minor changes were suggested, 20 respondents approved the list as presented. Thus, the author is certain that the list reflects real State concerns. It is emphasized that the ranked set of 11 should not be considered to have a relative or absolute scale.

It is concluded that this set of 11 ranked scenarios is sufficiently comprehensive and general enough to use in seeking a set of corresponding protective systems to incorporate into new and reconstructed highway systems.

Table 1. Ranked, generalized scenarios.

Rank	General Scenario Description
1	Poisonous, toxic, flammable or explosive material endangers large numbers of trapped motorists, e.g., between interchanges, in cut section, or in traffic jam downwind of poisonous or toxic gas release.
2	Chemical spills of poisonous or explosive materials that could enter underground "METRO" stations or transit tunnels through sidewalk vents, etc. (Includes entry of lighter-than-air toxic or poisonous gases into adjacent or overhead transit stations.)
3	Hazardous materials accidents causing release of toxic, flammable, or explosive materials in tunnels.
4	Gasoline, LNG, propane (flammables, explosive gases), etc., accidents and releases on elevated facilities, including ramps thereto, with people at risk below or in adjacent buildings.
5	Release of poisonous, toxic, or explosive gases in populated areas in general and/or in locations and situations where special populations and/or institutions such as schools, hospitals, hotels, nursing homes, apartment complexes, etc., are at risk.
6	Release from accidents between hazardous materials containers on highways and passenger trains or trains carrying hazardous cargo either at rail-highway crossings at grade or in situations with shared rights-of-way, such as freeways with transit in the median.
7	Explosive materials in facilities in populated areas, and particularly in situations and areas where catastrophic consequences could occur to highway structures or apartments--adjacent or on air rights. Includes situation with adjacent petro-chemical plant that could result in conflagration.
8	Sufficient quantities of poisonous materials, such as herbicides or dangerous biological/agents (or any material causing long-term or permanent damage) being released into a potable water supply, particularly reservoirs and susceptible aquifers and/or watersheds.
9	Rural, hilly, or mountainous areas with cities or towns at bottom of long or steep grades where brake failure of hazardous materials carriers could cause catastrophic consequences to the populated area.
10	Spills of nuclear wastes or other nuclear materials, particularly in populated areas, areas affecting water supply, or areas particularly difficult to respond to and/or clean up.
11	Carriers of toxic, flammable, or explosive materials leaking material during transit in heavily populated or congested areas.

Each State must rework this list to make it State-specific. For example, any given State should take one of the following actions with the list:

- Confirm that it applies as is.
- Reorder the priorities of the scenarios.
- Add scenarios that are unique to the State in priority order.
- Delete scenarios that do not apply.
- Break each generalized scenario down into State- and site-specific problems that are known to exist.
- Relate specific problems to highway elements (see section below on Catastrophic Potential Rated by Geometric Elements of Highways).

The above items are not mutually exclusive and combinations of these six actions may be appropriate. A State needs to start with such a list to alert its planners/designers to scenarios that might benefit from protective systems. The result should be a State check list of highway sections to consider for risk analysis and possible protective systems. The types of protective systems to be considered will be listed in chapter II, section B. Some example systems are presented in detail in chapter III.

One part of the study tied highway geometric elements to potentially catastrophic situations. The greatest perceived danger is from elevated facilities, followed by depressed facilities with development over (air-rights structures) and, lastly, receptors adjacent to the facility. As one panelist put it, "a hazardous material (hazmat) release can only go up, down or laterally." The panel rated their catastrophic potential in that order. These results can be seen in table 2. All ratings were done according to the key shown in table 3.

In regard to adjacent facilities, nursing homes or hospitals received the highest rank for catastrophic potential, followed by schools, apartments, shopping centers, hotels, factories, and hazmat storage facilities. The authors believe that hazmat storage facilities should have had a higher ranking, perhaps number 1, because they can have a chain-reaction, multiplying effect that perhaps was overlooked by the respondents.

Table 2. Generalized summary of round 4 results.[1]

Rank	Approx. Avg.[2] Mean Score	Generalized Highway Facility
1	5.6+	Elevated facilities with development below
2	5.5	Depressed facilities with development over
3	5.0 to 5.4	Any facility adjacent to vulnerable population in order of: a) Nursing home or hospital. b) Schools. c) Apartments. d) Shopping center. e) Hotel. f) Factory. g) Hazmat storage facilities.
4	4.0	Drainage into sewage system

[1]Round 4 was a rating of facility descriptors (as listed in table 4).
[2]Based on 1-7 scale explained in table 3.

Table 3. Key to scale values.

Scale Value[1]	Key
1	Very minor incident; of little or no consequence under normal conditions.
2	Minor incident; little chance of escalation, little danger to life or serious or long-term environmental damage (aquifer, reservoir, or water supply) unless grossly mismanaged.
3	Potentially dangerous incident; but not likely catastrophic, danger to life or environment (aquifer, reservoir, or water supply) only if not handled properly.
4	Neutral; no clear catastrophic potential yet hard to predict.
5	Definitely dangerous incident; could be catastrophic under certain conditions of traffic, weather, or inadequate response. Could easily escalate to catastrophic situation.
6	Very dangerous incident; high catastrophic potential, high probability of loss of life, serious injury, or long-term damage to environment (particularly aquifer, reservoir, or water supply).
7	Definitely catastrophic incident; loss of life, serious injury, serious damage to environment (particularly aquifer reservoir, or water supply) is certain to be avoidable only with extreme good luck.

[1]In general terms, where all replies are averaged, a mean value greater than 4 was interpreted to mean the scenario is catastrophic or had catastrophic potential.

3. Catastrophic potential of specific materials

In developing scenarios, risk analysis models and related protective systems, it was not practical to work with all hazmat or even with all 22 classes of materials. The advisory panel was polled as to what materials should be included. With input from the panel, six materials were selected to represent all common material consequences, and the study worked with these: chlorine (CHL), propane (PRO), anhydrous ammonia (AA), gasoline (GA), nitric acid (NA), and phosphorous compound (PH). These six materials were chosen because their combined properties and consequences represent nearly all hazardous materials.

A statistical analysis comparing mean scores of all possible pairs showed chlorine was ranked significantly higher than all other materials but there was no significant difference pairwise between any of the other materials. The conclusion drawn from this analysis is that chlorine is perceived to have greater catastrophic potential than the other five materials.

4. Catastrophic potential rated by geometric elements of highways

To better relate catastrophic occurrences to highway facility descriptors (e.g., geometric elements such as an elevated-to-lower-level-ramp), a set of the six specific materials (CHL, PRO, AA, GAS, NA and PH) with one highway facility descriptor set for each of six materials was sent to the panel members. (Table 5 shows such a set.)

Responses to the facility descriptors were too detailed to be the primary set of scenarios but give added direction to the expansion of the ranked set and a checklist of site-specific applications of the decision/risk model. The summary of responses and scores for all materials are shown in table 4. Table 5 summarizes the responses for gasoline. A similar summary was done for each of the six materials.

The responses to show the greatest concern is for released hazmat that goes down, e.g., from an elevated facility; next, for materials that go up, e.g., fires and explosions under overpasses and air-rights structures; and, lastly, by materials that go laterally, e.g., fire and gases that endanger adjacent lateral populations such as high-rise apartments, schools, hospitals, etc. These findings are entirely consistent with the 11 ranked scenarios.

Table 4. Ranked facility descriptors from round 4 from overall ranking of all six materials.

Rank	Components
1	elevated basic segment over shopping center
2	elevated weaving area (non-ramp) over shipping center
3	elevated ramp/ramp junction/acdl.-decel. lanes over shipping center
4	depressed basic segment with air-rights development
5	depressed weaving area with air-rights development
6	elevated, at-grade depressed (nothing over or under) basic segment within one block of nursing home or hospital
7	depressed ramp/ramp junction with air rights development
8	elevated, at-grade or depressed (nothing over or under) weave section (within one block of) nursing home or hospital
9	elevated, at-grade or depressed (nothing over or under ramp/ramp junction/accel.-decel./lanes within one block of nursing home or hospital
10	elevated, at-grade or depressed (nothing over or under) basic segment (within one block of) school)
11	elevated at-grade or depressed (nothing over or under) basic segment (wihtin one block of) school
12	elevated, at-grade or depressed (nothing over or under) ramp/ramp junction/accel.decel/lanes within one block of school
13	elevated, at-grade or depressed (nothing over or under) basic segment (within one block of) apartments
14	elevated basic segment over parking
15	elevated ramp/ramp junction/accel.-decel. lanes over parking
16	elevated weaving area (non-ramp) over parking
17	elevated, at-grade or depressed (nothing over or under) basic segment (within one block of) shopping center
18	elevated, at-grade or depressed (nothing over or under) basic segment (within one block of) factory
19	elevated, at-grade or depressed (nothing over or under) basic segment (within one block of) apartments
20	elevated, at-grade or depressed (nothing over or under) weave section (within one block of) hotel
21	elevated, at-grade or depressed (nothing over or under) basic segment (wihtin one block of) office building
22	elevated, at-grade or depressed (nothing over or under) ramp/ramp junction/accel.-decel./lanes within one block of apartments
23	elevated, at-grade or depressed (nothing over or under) ramp/ramp junction/accel.-decel./lanes within one block of factory
24	elevated, at-grade or depressed (nothing over or under) weave section (within one block of factory
25	elevated, at-grade or depressed (nothing over or under) weave section (within one block of) shopping center
26	depressed drainage into storm sewer
27	elevated, at-grade or depressed (nothing over or under) ramp/ramp junction/accel.-decel./lanes within one block of shopping center
28	depressed drainage into combined sewer
29	elevated, at-grade or depressed (nothing over or under) weave section (within one block of) hotel

Table 4. Ranked facility descriptors from round 4 from overall ranking of all six materials (continued).

Rank	Components
30	elevated, at-grade or depressed (nothing over or under) ramp/ramp junction/accel.-decel./lanes within one block of office building
31	elevated drainage (from el.) to storm sewer
32	elevated drainage (from el.) to combined sewer
33	at-grade drainage into storm sewer
34	at-grade or depressed (nothing over under) ramp junction/accel.-decel./lanes within one block of hotel
35	elevated, at-grade or depressed (nothing over or under) weave section (within one block of) office building
36	at-grade drainage into combined sewer
37	at-grade basic segment
38	at-grade weaving area (non-ramp)
39	at-grade ramp/ramp junction/accel.-decel. lanes
40	depressed ramp/ramp junction without air-rights development
41	depressed weaving area without air-rights development
42	depressed basic segment without air-rights development
43	elevated, at-grade or depressed (nothing over or under) basic segment (within one block of) storage of hazardous materials
44	elevated, at-grade or depressed (nothing over or under) weave section (within one block of) storage of hazardous materials
45	elevated, at-gade or depressed (nothing over or under) ramp/ramp junction/accel.-decel./lanes within one block of storage of hazardous material
46	elevated basic segment no development under
47	elevated weaving area (non-ramp) no development under
48	elevated ramp/ramp junction/accel.-decel. lanes no development under

Table 5. Results of the rating value for catastrophic potential of various highway segments for gasoline.[1]

Gasoline: faculty descriptor/reactor catastrophic potential response

Mean Rating[2]	Urban Freeway Components		
	a. elevated	(1)	basic segment
5.52			(a) over shopping center
5.04			(b) over parking
3.93			(c) no development under
		(2)	weaving area (non-ramp)
5.52			(a) over shopping center
5.04			(b) over parking
3.93			(c) no development under
		(3)	ramp/ramp junction/accel.-decel. lanes
5.52			(a) over shopping center
5.04			(b) over parking
3.93			(c) no development under
5.08		(4)	drainage (from el.) to storm sewer
5.04		(5)	drainage (from el.) to combined sewer
4.44	b. at-grade	(1)	basic segment
4.44		(2)	weaving area (non-ramp)
4.33		(3)	ramp/ramp junction/accel.-decel. lanes
4.83		(4)	drainage into storm sewer
4.93		(5)	drainage into combined sewer
	c. depressed	(1)	basic segment
5.15			(a) with air-rights development
4.37			(b) without air-rights development
		(2)	weaving area
5.22			(a) with air-right development
4.44			(b) without air-right development
		(3)	ramp/ramp junction
5.19			(a) with air-rights development
4.41			(b) without air-rights development
4.67		(4)	drainage into storm sewer
4.707		(5)	drainage into combined sewer
	d. elevated, at-grade or depressed (nothing over or under)		
4.59		(1)	basic segment (within one block of)
4.59			(a) apartments
4.63			(b) school
4.74			(c) nursing home or hospital
4.56			(d) shopping center
4.56			(e) hotel
4.59			(f) office building
4.52			(g) factory
4.37			(h) storage of hazardous materials

[1]Additional statistics presented in volume I.(3)
[2]Based on 1-7 scale explained in table 3.

Table 5. Results of the rating value for catastrophic potential of various highway segments for gasoline (continued).[1]

Gasoline: faculty descriptor/reactor catastrophic potential response

Mean Rating[2]	Urban Freeway Components
	(2) weaving sections (within one block of)
4.63	(a) apartments
4.67	(b) school
4.78	(c) nursing home or hospital
4.59	(d) shopping center
4.59	(e) hotel
4.63	(f) office building
4.56	(g) factory
4.37	(h) storage of hazardous materials
	(3) ramp/ramp junction/acel.-decel./lanes (within one block of)
4.63	(a) apartments
4.67	(b) school
4.78	(c) nursing home or hospital
4.59	(d) shopping center
4.59	(e) hotel
4.63	(f) office building
4.59	(g) factory
4.24	(h) storage of hazardous materials

[1]Additional statistics presented in volume I.(3)
[2]Based on 1-7 scale explained in table 3.

In regard to adjacent facilities, nursing homes or hospitals received the highest rank for catastrophic potential, followed by schools, apartments, shopping centers, hotels, factories, and hazmat storage facilities.

The study showed little significant difference between materials, indicating that, for the materials given, the location of the incident was generally perceived as being more important than the material. Table 2 shows how the respondents ranked receptor facilities adjacent to highways. Based on the analysis of results described above, the highway facility descriptor scenarios (HFDS) appear to be independent of material type and more dependent on the "down, up, or lateral" movement concept. Location of the incident insofar as affected populations are concerned is, or at least is perceived to be, the controlling factor.

5. Environmental scenarios

When the original scenarios were returned by the States' panel, only a very few were related to environmental problems. However, this is the number one concern of communities all over the United States.[4] Advisory panel contracts in New York, Minnesota, and Rhode Island noted the potential for contamination of reservoirs or aquifiers is a major concern in these States.

Some experts believe the public's greatest fear is contamination of water supplies.[4] A separate round of questions was sent to the panel dealing only with environmental issues. The results are shown in table 6. The results can be considered a supplement to generalized scenario number 8 (table 1).

Any of the 11 scenarios could be subdivided into more specific cases, such as the round 5 results subdivided the environmental category. A State may wish to do so, and in fact, should do so in the process of making the generalized scenarios State-specific. This should assist in development of a risk assessment model, refined for a particular State- or site- and material-specific incident. A risk analysis framework presented in the next section of this volume will guide a State in the process.

B. Protective Systems Development

1. Panel survey for protective system ideas

Development of the prioritized scenarios has been summarized in the previous section. After ranking the 11 prioritized extreme risk scenarios,

Table 6. The round 5 environmental scenario questionnaire and the summary of results.[1]

Mean Rating[2]		
	1.	Direct spill into potable water supply
5.78		(a) Reservoir - direct spill
5.59		(b) Aquifer - little or no soil cover
4.31		(c) Aquifer - soil cover > 25 ft.
4.13		(d) Area of wells; within 1 mi
	2.	Spill into waterbed or stream within one mile
4.88		(a) Reservoir
4.69		(b) Aquifer
	3.	River
5.00		(a) Immediately upstream of urban area
		(b) Rural
	4.	Stream
4.31		(a) Rural
4.47		(b) Urban
4.00	5.	Crop land
3.68	6.	Open ground, agricultural
	7.	Open ground, non-agricultural
4.00		(a) High runoff
4.03		(b) High permeability
4.22		(c) Sinkhole area
3.96	8.	Ecosystem flora, fauna
	9.	Sewage drainage system
4.00		(a) Rural
4.25		(b) Urban
	10.	Storm water
4.13		(a) Rural
4.28		(b) Urban

[1]Additional statistics presented in volume I.(3)
[2]Based on 1-7 scale explained in table 3.

the next task was to develop "feasible, implementable, and practical" protective systems keyed to them.

Deciding what were feasible, implementable, and practical protective systems proved to be very difficult. It was concluded that the practical aspect of the protective systems was the key criterion. This can only be decided by an individual State taking into account its risk vs. the cost-benefit of the protective system within the context of overall State priorities and resources. It is a management decision. Ideally, benefit should be measured in terms of risk reduction, but this would be very elusive indeed because the data necessary to do a meaningful risk reduction analysis on previously untried protective systems is not available. Accident reduction values will, initially, have to be based on judgment of traffic engineers with expertise in accident causation.

The States' advisory panel, formed for the purpose of scenario development and ranking, was again utilized. The last round of the scenario prioritization process asked the panelists to present ideas on protective systems keyed to each of the 11 scenarios.

Although some panelists responded to some scenarios with comments such as "no hope" and left some blank, several good ideas were returned for all scenarios. These were sorted, edited, and sent back to the panel. Editing was very slight to keep the ideas essentially as the panelists had presented them.

Many panelists felt regulatory-type solutions were the best option, even after being told that they should not be included. Thus, they are presented with the results. This is discussed below.

The key to the 1 to 7 rating scale the panelists were asked to use is presented in table 7. Thirty-two responses were analyzed and the mean, standard deviation, maximum, and minimum scores of each protective system were calculated.

Communications and automatic detection systems were mentioned in the responses to almost all scenarios. Exploratory work was done on such systems and specific examples of these were sent out separately.

2. Philosophy of analyzing results

Protective system responses were so varied that it was not immediately clear how to interpret the results. Mean responses for all protective systems

Table 7. Key to scale values--systems.

Scale Value[1]		Key Guidelines to Assist Raters
Bad (Worst)	1	Nearly impossible to implement, not at all practical, will serve no useful purpose
	2	Very difficult to implement; little value
	3	Difficult to implement; some value possible but probably not worth the effort or cost
"Neutral"	4	Hard to judge; not clearly "good" or "bad" idea
	5	Possible merit as practical and implementable protective system; worth further thought or development
	6	Clear cut merit as practical and implementable protective system
Excellent (Best)	7	Highly feasible, very practical, useful and efficient, excellent and very desirable

[1]In general terms, where all replies are averaged, a value less than 4 would suggest that the idea would be highly difficult to design/ construct and install or would not be very useful/desirable; i.e., throw it out.

varied from less than 2.0 to 5.3, and there are large differences between responders to the same protective systems for the same scenarios. The range on almost all individual protective systems was 1 to 7.

The next decision was to determine high and low mean values. There was no rational way to determine anything but an arbitrary cut-off point, such as listing the protective systems from highest to lowest and selecting a reasonable number of them from the top that could be handled well with the available project resources. A mean rating of 4.0 was chosen as the cut-off point.

All protective systems with a mean rating of 4.0 or greater are presented in table 8, categorized by the 11 scenarios. The last group of protective systems in table 8 is a summary of communication and detection systems that were suggested and ranked highly for many of the scenarios. These results can be seen in table 9.

Table 8. Protective system rating results of all proposed protective systems rated 4.0 or greater.[1]

SCENARIO 1 -- Poisonous, toxic flammable or explosive material endangers large numbers of trapped motorists, e.g., between interchanges, in cut section or in traffic jam downwind in poisonous or toxic gas release.

Protective Systems-type Solutions

Rank	Mean	
1	5.1	Traversable medians
2	5.0	Emergency phone call boxes on all hazardous cargo routes
3	4.7	Crossovers
3	4.7	Median openings
4	4.6	Highway exits designed for traffic entrance (response team) from opposite direction

Regulatory-type Solutions

Rank	Mean	
R1	5.2	Routing restrictions
R2	5.0	Prohibition on hours (curfews)
R2	5.0	Prohibit large trucks through congested areas (routing)

SCENARIO 2 -- Chemical spills of poisonous or explosive materials that could enter underground "METRO" stations or transit tunnels through sidewalk vents, etc. (Includes entry of lighter-than-air toxic or poisonous gases into adjacent or overhead transit stations.)

Protective Systems-type Solutions

Rank	Mean	
1	5.4	Fresh air vents at elevated levels
1	5.4	Prohibition in areas; air vents--intakes away from roads, arrows in tunnels with distance to exit, etc.
3	4.2	Coamings over street-level in-take vents with drainage away from vents. For overhead stations, the ability to crash-stop ventilation and provide positive internal pressure.
3	4.2	Pea-trap system vents to trap gases in first section

Regulatory-type Solutions

Rank	Mean	
R1	4.8	Restricted routing in these areas

---

[1]Additional statistics presented in volume I.(3)

Table 8. Protective system rating results of all proposed protective systems rated 4.0 or greater (continued).[1]

SCENARIO 3 -- Hazardous materials accidents causing release of toxic, flammable or explosive materials in tunnels.

Protective Systems-type Solutions

Rank	Mean	
1	6.0	Arrows pointing to nearest exit
2	5.8	Effective vent systems
3	5.5	Monitoring for quick response
4	5.2	Gas detectors/alarm systems
5	4.9	Large sprinkler systems
6	4.0	Emergency exits with heavy doors

Regulatory-type Solutions

Rank	Mean	
R1	5.9	Routing hazmats away from tunnels (prohibition)

SCENARIO 4 -- Gasoline, LNG, propane (flammables, explosive gases), etc., accidents and releases on elevated facilities, including ramps there-to, with people at risk below or in adjacent buildings.

Protective Systems-type Solutions

Rank	Mean	
1	4.9	High performance barrier/rail systems, to prevent such an accident
2	4.8	Avoid use of open rails on structure
3	4.4	Robust drainage with holding reservoirs that can be isolated from regular storm drains (and later pumped) should a spill occur
4	4.2	Conduit railing for automatic spraying of water
4	4.2	Relocate or close ramps--in critical locations; install improved barriers; prohibit truck use of such ramps

Regulatory-type Solutions

Rank	Mean	
R12	5.3	Reduced speed
R2	4.3	No hazmat through high urban area (prohibition)

[1] Additional statistics presented in volume I.[3]

Table 8. Protective system rating results of all proposed protective systems rated 4.0 or greater (continued).[1]

SCENARIO 5 -- Release of poisonous toxic or explosive gases in populated areas in general and/or in locations and situations where special populations and/or institutions such as schools, hospitals, hotels, nursing homes, apartment complexes, etc., are at risk.

Protective Systems-type Solutions

Rank	Mean	
1	4.5	Communication and detection systems
2	4.3	Development of a public notification system for efficient evacuation possibly using air raid type alarms and public address systems.

Regulatory-type Solutions

Rank	Mean	
R1	6.0	Evacuation planning
R2	5.9	Emergency response training
R3	5.5	Reduced speed with strict enforcement
R4	5.4	Routing/prohibition
R4	5.4	Training of personnel of schools, hospitals, hotels, nursing homes

SCENARIO 6 -- Releases from accidents between hazardous materials containers on highways and passenger trains or trains carrying hazardous cargo either at rail-highway crossing at grade or in situations with shared rights-of-way, such as freeways with transit in the median.

Protective Systems-type Solutions

Rank	Mean	
1	4.8	Installing effective barriers between parallel transport corridors
2	4.7	Shared rights-of-way should be separated by concrete barriers
3	4.6	Higher, stronger, etc., barriers next to transit

Regulatory-type Solutions

Rank	Mean	
R1	6.1	Specific training for fire department, police, etc.
R2	5.5	State-of-art crossing warning systems
R3	5.3	Reduced train speeds in urban areas
R4	5.0	Sufficient warning indicators installed reasonably well in advance of crossings
R5	4.7	Restricting hazmat transportation routes to avoid high hazard areas
R6	4.3	Law requiring full stop before crossing

[1]Additional statistics presented in volume I.[3]

Table 8. Protective system rating results of all proposed protective systems rated 4.0 or greater (continued).[1]

SCENARIO 7 -- Explosive materials in facilities in populated areas and particularly in situations and areas where catastrophic consequences could occur to highway structures or apartments adjacent or on air rights. Includes situation with adjacent petro-chemical plant that could result in conflagaration.

Protective Systems-type Solutions

Rank	Mean	
1	4.5	Communication and detection systems

Regulatory-type Solutions

Rank	Mean	
R1	5.8	Increase inspections
R2	5.8	Insure inspection and regulation of storage facilities
R3	5.4	Escort vehicle for explosives
R3	5.4	Control speed
R5	5.3	Mandate restrictive zoning prohibiting certain chemical storage/processing around certain traffic/population density situations
R4	5.3	Zoning restrictions to avoid population build ups in such areas; i.e., planning of industrial park siting being cognizant of the raw materials and products that will be kept in storage
R5	5.0	Routing/prohibition
R6	4.5	Thermal protective coverings on packages

SCENARIO 8 -- Sufficient quantities of poisonous materials, such as herbicides, or dangerous biological/agents (or any material causing long-term or permanent damage) being related into a potable water supply, particularly reservoirs and susceptible aquifers and/or watersheds.

Protective Systems-type Solutions

Rank	Mean	
1	4.8	Drainage gutters to direct spilled material toward collection point
2	4.7	Design with clay blanket or barrier membrane; direct drainage away from sensititve areas
3	4.5	Floating surface barrier (for insoluble petroleum oils)

---

[1]Additional statistics presented in volume I.[3]

Table 8. Protective system rating results of all proposed protective systems rated 4.0 or greater (continued).[1]

Protective Systems-type Solutions

Rank	Mean	
4	4.4	Robust drainage with holding reservoirs that can be isolated from regular storm drains should spill occur
5	4.2	Large sumps
5	4.2	Retention basin that can automatically close to capture spillage
6	4.0	Grease trap sedimentation basin (for heavier insolubles)

Regulatory-type Solutions

Rank	Mean	
R1	5.9	Insure inspection and regulation of storage facilities

SCENARIO 9 -- Rural, hilly or mountainous areas with cities or towns at bottom of long or steep grades where brake failure of hazardous material carriers could cause catastrophic consequences to the populated area.

Protective Systems-type Solutions

Rank	Mean	
1	6.0	Truck escape ramp
2	5.6	Upgrade runoffs for deceleration and extra-wide shoulders
3	4.4	Construct massive barrier and put energy absorbing material in front

SCENARIO 10 -- Spills of nuclear wastes or other nuclear materials, particularly in populated areas, areas affecting water supply, or areas particularly difficult to respond to and/or clean up.

Protective Systems-type Solutions

Rank	Mean	
1	4.7	Drainage gutters to direct spilled material toward collection point
2	4.5	Robust drainage with holding reservoirs that can be isolated from regular storm drains should spill occur
3	4.2	Large sumps
3	4.2	Design with clay blanket or barrier membrane; direct drainage away from sensitive areas

---

[1]Additional statistics presented in volume I.(3)

Table 8. Protective system rating results of all proposed protective systems rated 4.0 or greater (continued).[1]

Regulatory-type Solutions

Rank	Mean	
R1	5.9	Strict monitoring of drivers and equipment (e.g., at truck weigh stations)
R2	5.6	Routing restrictions for such materials
R3	5.4	Escort shipments

SCENARIO 11 -- Carriers of toxic flammable or explosive materials leaking material during transient in heavily populated or congested areas.

Protective Systems-type Solutions

Rank	Mean	
1	4.3	Communication and detection systems

Regulatory-type Solutions

Rank	Mean	
R1	6.2	Intensive motor carrier enforcement program putting such vehicles out of service until repaired
R2	5.7	Inspection stations for carriers of hazmats
R3	5.2	Restricted route and curfews
R4	4.7	Cleanup materials on each truck to absorb/neutralize spills

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[1]Additional statistics presented in volume I.(3)

Table 9. Scenario--all scenarios, summary of communication and detection systems.

A. Detection

1. Non-Remote Sensing Techniques, general:

Mean Score	Rank	Specific Examples
5.9	1	Explosimeters
5.8	2	Colorimetric Indicators
5.4	3	TLV Sniffers
5.1	4	Water Analysis Kits

2. Remote Sensing, general:

Mean Score	Rank	Specific Examples
6.7	1	Gaseous-measuring laser radar systems (termed differential absorption lidar)
6.5	2	Plume and Haze analyzer
6.5	2	U.S. Army's remote sensing XM 21 (modified version for hazardous material detection)
6.0	4	Correlation spectrometer
5.8	5	Miehelson interferometer (eq. U.S. EPA's Remote Official Spectrometer for Emissions)
5.8	5	Van-mounted lidar
5.8	5	Aircraft-mounted lidar
5.3	8	Thermal Sensing

B. Communication

Mean Score	Rank	Specific Examples
6.3	1	Instructions available with all drivers
5.5	2	Radiation indicators on trucks
5.4	3	Instructions pasted on truck's body
5.3	4	Posted standard instructions regarding nature of hazard, preliminary protective measures, and first aid
5.2	5	Gas detectors
4.9	6	Telephone booths
4.7	7	Remote sensing alarms

3. Results

One general conclusion could be readily seen from the results. Communication and detection type protective systems rated very highly. The communication and detection section of the questionnaire was clearly marked optional for those who felt qualified to respond. Only a few panelists responded, but the mean rating was generally very high, as seen in table 9. Communication and detection systems would be site-specific protective systems; i.e., high-risk, high catastrophic potential situations of a particular nature and not for general use.

Research and development, beyond the scope of this study, is needed to adapt these to site-specific highway situations. Suppliers and manufacturers would have to be contacted about site-specific or scenario-specific situations. (See chapter IV for additional information.)

4. Regulatory-type responses

A summary of regulatory-type solutions compared to protective system type responses is presented in table 10. Even though it was made clear to the panel that they were not within the scope of the project, almost as many regulatory-type solutions to the scenarios were returned and ranked generally higher than protective system-type ideas. From table 10, a summary of the number of solutions for each category of panel solutions, protective system type and regulatory type, the latter emerge as a dominant factor. Thirty-four of the 76 total solutions rated 4.0 or above (45 percent) were of the regulatory type. The overall mean rating of the regulatory type was 5.3, compared to 4.7 for the protective system type. Responses to 9 of the individual scenarios show that the regulatory type were rated higher in every case. Of the other two, scenario number 2 was a tie (4.8), and scenario number 9 had no regulatory type solutions proposed.

5. General conclusions of the research study

Based on responses of a large panel representing a broad cross-section of States' concerns, regulatory type preventative measures dominate suggested solutions and should be considered. Conversely, it can be concluded that the physical, protective system concept is not applicable as a general preventive or mitigating approach. It is limited to a few site-specific, high-risk situations where the protective system approach is clearly effective, and the

Table 10. Summary of regulatory-type solution compared to protective system-type responses of all proposed ideas 4.0 or greater.

Scenario	Protective System-type No.	Protective System-type Mean Score	Regulatory-type No.	Regulatory-type Mean Score
1	5	4.8	3	5.1
2	5	4.8	1	4.8
3	6	5.2	1	5.9
4	5	4.5	2	4.8
5	2	4.4	5	5.6
6	3	4.7	6	5.2
7	1	4.5	8	5.3
8	7	4.4	1	5.9
9	3	5.3	0	---
10	4	4.4	3	5.1
11	1	4.7	4	5.3
OVERALL	42	4.7	34	5.3

risk is deemed high enough to offset the cost. This is a policy decision of each individual State, and this decision is the heart of the practicality criterion.

6. Physical, protective systems

The analysis of the results found only one type of protective system that could be called preventive. This type consists of various barriers to contain a hazmat vehicle on or within the roadway to prevent loss of control and its going off an overhead facility, off a ramp, into a school yard, etc. Various types of barrier rail designed to contain large trucks and truck escape ramps would be typical of this category.

All others can be classified as mitigating. This type dominates the responses. It includes categories such as detection and warning systems, systems to facilitate escape and response, systems to mitigate fire/explosion consequences, systems to mitigate spill consequences, and systems related to highly specialized situations, such as elevated METRO vents. A few of the physical, protective systems included in table 9 could possibly fit more than one category, but each should fit predominantly into one. They are so categorized in table 11.

Considering all input into the scenario development and protective system survey and rating, the key to guidelines is a manual pointing out areas of

Table 11. Categorization of proposed physical, protective systems for highways.

Category		System
	I. MITIGATING	
A.	Detection and Warning	Built-in PA systems Emergency call boxes Gas detectors/alarms Monitoring for quick response Communication and detection systems
B.	Systems to Facilitate Escape and Response	Crossovers Transversable medians Median openings Highway exit/entrance redesign for emergency response vehicles Emergency exits with heavy doors (tunnels) Arrows pointing to nearest exit (tunnels)
C.	System to Mitigate Fire/Explosion Consequences	Foam blanketing systems Large sprinkler systems Effective vent systems
D.	Systems to Mitigate Spill Consequences	Pea-style vents to trap gases Effective vent systems (closed areas) Robust drainage with holding reservoirs Avoid use of open rails on structures Large sumps Grease trap sedimentation basins Floating surface barriers Drainage gutters directed toward collection points Retention basins that automatically close Clay blankets or barrier membranes
E.	Specialized Situations	Fresh air vents at elevated levels (METRO) Coamings over street-level intake vents (METRO) Air intake away from roads (tunnels, METRO) Massive barriers with energy absorbing material (runaway trucks)
	II. PREVENTATIVE	
A.	Containment	High performance barrier systems
B.	Control	Truck escape ramps Upgrade truck runoffs Wide shoulders

general solutions that should be considered, rather than a design manual that attempts to set forth standards that must be followed. Table 11 is a checklist that can be used as a starting point. Protective system examples are discussed in chapter III in more detail.

The next step in a State's decision-making process is to determine if the risk is high enough to consider protective systems and if a risk-effective or cost-effective protective system is available. A recommended risk analysis procedure is presented in section c. However, each State must decide what level of risk is "too high" and what level of reduction per unit expenditure of funds is cost-effective. Also, risk reduction values for a given protective system will mostly be based on judgement.

C. Recommended Risk Model Procedure[1]

After review of all of the currently available alternatives, it is recommended that the FHWA risk analysis techniques be used as a basis since they are the best practical tools available today for State use in determining risk of highway transportation of hazardous materials. The model is not the most analytically rigorous or mathematically sophisticated, nor the best research tool, but it is usable, understandable and adaptable to most existing and/or obtainable data bases.

Most States' data bases are lacking. They need to be examined and enhanced through additional data acquisition on hazardous materials flows to allow for really good risk analysis. The FHWA model can easily be made more rigorous or sophisticated over time as data quantity and quality improves. Any State's risk analysis value is a function of the resources it is willing to put into data collection. Data collection will be addressed later in this section. The model has recently been improved and a report with recommendations for improvement will be issued by the FHWA in 1989.[2] A summary of the significant improvements are included in this section.

The model can be used for a macro-analysis of statewide routes, a macro- or micro-analysis of regional or community routes and a micro-analysis of various segments, although caution must be used as discussed below. The reliability of the results lie in the availability and accuracy of appropriate data. Assuming that the proper data is available or obtainable, good results can be expected.

[1]This section is based on summaries and excerpts from reference 2.

Volume I of this study reviews other risk models along with their data needs. Efforts could be redirected toward using other models or incorporating additional sophistication into the FHWA model if desirable and consistent with a State's data.

The remainder of this chapter will be a summary of the current FHWA model as it exists in the 1980 FHWA Routing Guidelines and changes that should be considered.[1,3] This discussion is presented so that those familiar with the 1980 Routing Guide will know what changes are being recommended. The final report of the recent FHWA study includes a detailed critique of the existing FHWA model and the rationale for numerous suggested changes.[3] It is recommended that the user also obtain and study this report. A summary of this critique and recommended revised procedures from this report is presented below in sections 3 and 4 below.

1. Overview of the 1980 FHWA routing method[1,2,3]

The 1980 Routing Guide presented the most widely used risk assessment procedure for highway transportation of hazardous materials. The key element of this method is a risk assessment model known to many as the Urbanek model. Figure 1 illustrates the structure of the FHWA routing method.

Prior to the application of the risk assessment model, the alternative routes under consideration were evaluated by two types of mandatory factors: physical and legal factors. The physical factors are those that might make a particular alternative route unfeasible, such as weight restrictions on bridges or height restrictions at underpasses. Other physical contraints might include inadequate shoulders for breakdowns, extensive construction activities, or inadequate parking and turning spaces. Legal factors that could limit the feasibility of a particular alternative route include laws and regulations prohibiting trucks or hazardous materials on specific roadways, bridges, tunnels, or toll roads. Alternative routes found to be unfeasible due to physical or legal factors should be eliminated from consideration very early in the process.

The next step in the FHWA routing method is conducting a quantitative evaluation of the alternative routes using the risk assessment model, which is discussed in a following section of this report. The output of this analysis is a risk estimate for each alternative route.

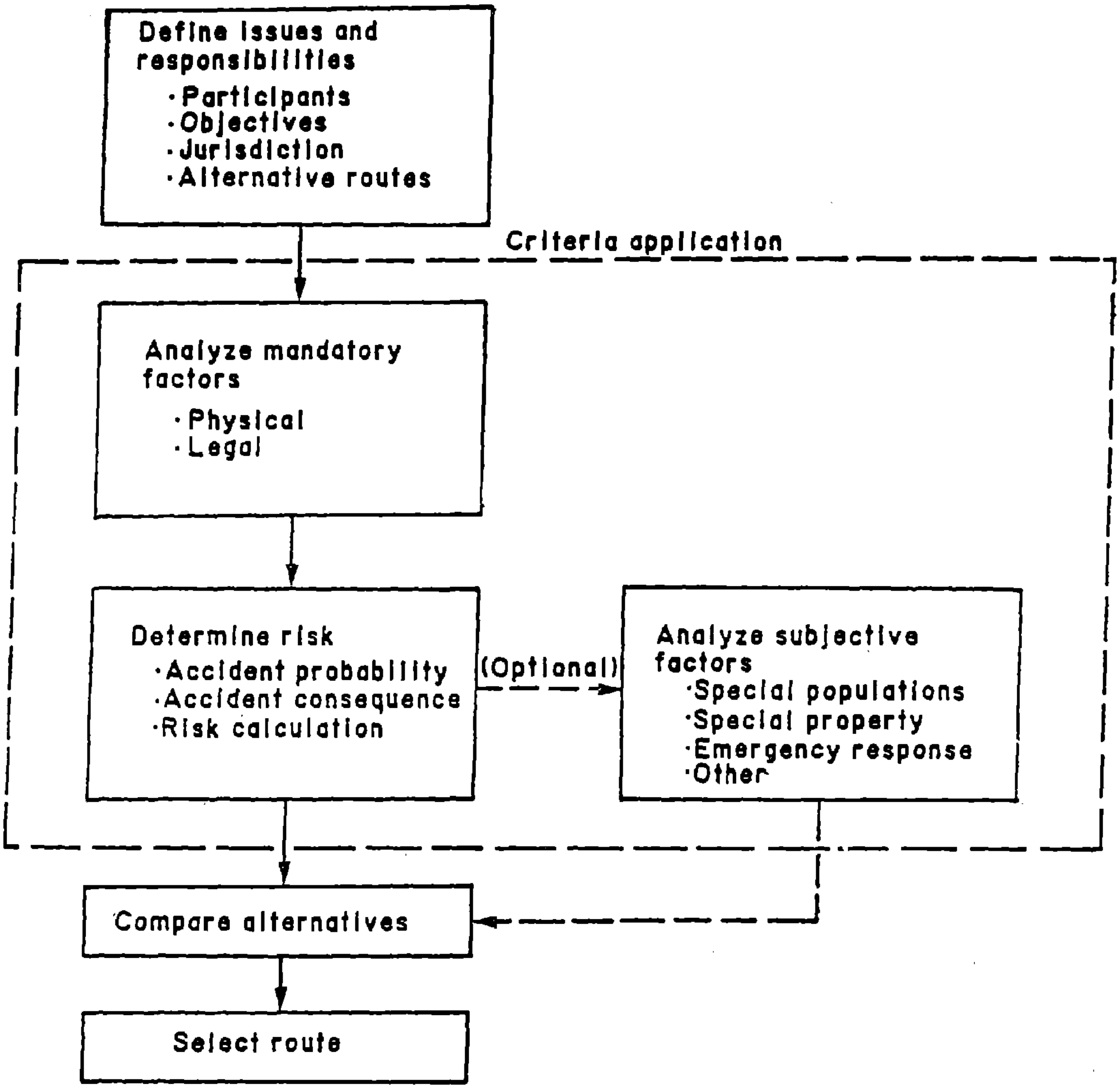


Figure 1. Structure of FHWA hazardous materials routing method.[1]

The final step in the FHWA routing method is considering subjective factors that cannot be easily quantified but may increase the consequences of a hazmat release on one route in relation to another. Most frequently considered are:

- Special populations such as schools, hospitals, nursing homes, etc.
- Sensitive environmental entities such as reservoirs, wildlife habitats.
- Hazardous materials storage facilities that could magnify consequences.

2. Overview of the FHWA risk assessment procedure[1,2,3]

The risk assessment procedure that is part of the 1980 FHWA Routing Guide is intended to compare the risks involved in hazmat transportation by highway on two or more selected alternative routes. In its most common application, this method is a relative assessment as routes are compared to each other. A risk number is calculated for each route, but the relative comparison of each number is considered more important than the number itself, which may or may not be realistic in terms of an absolute risk value. However, the risk number may be a measure of absolute risk if the data used is complete and accurate--by risk analysis standards. In many cases, the alternative routes being compared are not homogeneous by highway type, traffic volume, population density, or level of development; therefore, it is usually necessary to divide each alternative route into relatively homogeneous segments. A route's total risk is then determined as the sum of the calculated risks for all segments of that route.

There are three steps in the determination of risk using the model. These are:

- Determine accident probability.
- Determine accident consequences.
- Calculate risk.

Each of these steps is described below.

a. Determine accident probability: **The probability of a hazmat** accident is computed in the risk assessment model from the following equation:

$$P(A)_i = AR_i \times L_i \times FHZ \qquad (1)$$

where:

$P(A)_i$ = probability of a hazardous materials accident for route segment i;

AR_i = accident rate per vehicle-mile for all vehicle types on route segment i;

L_i = length (miles) for route segment i; and

FHZ = fraction of all accidents that involve a hazmat release.

b. Determine accident consequences: The risk assessment model considers two types of consequences from an accident involving a release of hazardous materials. These are personal injury consequences and property damage consequences. Both are compared between routes based on the population potentially exposed and the value of the property potentially exposed to a hazmat release.

The model assumes the personal injury consequences of a hazmat release are proportional to the population potentially exposed to the release. This concept of exposure as the consequence measure must be understood and accepted. The population potentially exposed to a release may be estimated on the basis of residential population, employment, motorists, or a combination of the three. A worst case or maximum number potentially exposed is commonly used. The application of the model to residential populations is illustrated in the 1980 Routing Guide. It assumes the whole population is occupying their respective facilities or space within the affected area. (Models estimating numbers killed, seriously injured, slightly injured, etc., are available; however, they are extremely complex and of questionable value when used with data typically available to State highway or transportation departments.)

Table 12 shows suggested impact distances to be used with the model. A State could refine these if desired (discussed in more detail in other paragraphs of this section).

A similar approach is used for the assessment of property damage consequences, considered to be an optional component of the risk assessment model. The property damage consequences of a hazmat release are assumed to be proportional to the value of the property adjacent to the route segment in question. The model considers only property adjacent to the roadway, not property within the entire impact zone for population risks defined above. The following five land-use types are considered by the model:

Table 12. Potential impact distance for various classes of hazardous materials.[1]

Hazardous Materials Class	Impact Distance[1]
Combustible Liquid (CL)	0.5 mi all directions
Flammable Liquid (FL)	0.5 mi all directions
Flammable Solid (FS)	0.5 mi all directions
Oxidizer (OXI)	0.5 mi all direction
Non-Flammable Compressed Gas (NFG)	Downwind 1.3 mi wide by 2 mi long
Flammable Compressed Gas (FG)	0.5 mi all directions
Poison (POI)	Downwind 0.2 mi wide by 0.3 mi long
Explosives (EXP)	0.5 mi all directions
Corrosive (COR)	Downwind 0.5 mi long by 0.7 mi wide

[1](1 mi = .621 km)

- High-density residential.
- Medium-density residential.
- Low-density residential.
- Commercial
- Industrial.

c. Calculate risks: Risk is calculated in the model as the product of the probability of a hazmat accident and the population or property damage consequences of an accident. Thus, in general:

$$\text{Risk} = \text{Probability} \times \text{Consequences} \quad (2)$$

The population risk is computed in the model as:

$$RPOP_i = P(A)_i \times POP_i \quad (3)$$

where:

$RPOP_i$ = population risk along route segment i;

$P(A)_i$ = probability of a hazardous materials accident for route segment i;

POP_i = a number of persons exposed to a hazardous materials release along route segment i.

The property damage risk is computed as:

$$RPD_i = P(A)_i \times PV_i \quad (4)$$

where: PV_i = property value along route segment i.

The total population risk or total property damage risk for each alternative route is computed by summing all of the individual risks along each route. The risk assessment model does not provide a method or suggest guidelines for combining or weighting the population and property damage risks for a route, so these risks must be considered separately.

A brief discussion of the rationale for changes recommended in a later section of the manual are presented below so that those familiar with the 1980 FHWA Routing Guide will better understand the basis of the revised model.

3. Basis of the revised risk assessment procedure[2]

Those revisions of importance to the procedure recommended in this manual are:

a. Basic formula: Equation (2) is the basic risk assessment formula in the guide. This equation is adequate for all practical purposes and should be retained. However, there is no accepted easy or practical method for estimating the consequences (i.e., persons injured or property damaged) by a hazmat release. The existing method assumes the consequences of a hazmat release are proportional to the number of persons or amount of property exposed to a release, and this assumption should be clearly understood in the analysis; the basic unit of risk in this approach is the number of persons exposed. This basic number could be per unit, per year, per hazmat truck passage, etc. This guide proposes "average person exposed per highway mile."

b. Accident probability: The computation of accident probability on a route segment should be revised to incorporate truck accident rate, segment length, and the probability of a hazmat release given a hazmat truck accident. Equation (1) should be replaced with the following relationship:

$$P(R)_i = TAR_i \times P(R/A)_i \times L_i \qquad (5)$$

where:

$P(R)_i$ = probability of an accident involving a hazmat release for route segment i;

TAR_i = truck accident rate (accidents per veh-mi) for route segment i;

$P(R/A)_i$ = probability of a hazmat release given an accident involving a hazmat-carrying truck for route segment i; and

L_i = length (length (miles) of route segment i.

c. Default values: Improved default values for truck accident rates (TAR_i) are a function of highway type and area type and should be developed by the State. As a minimum, reliable default truck accident rates are needed for the following types of highways:

- Rural freeways.
- Rural two-lane highways.
- Rural multilane divided highways.
- Urban freeways.
- Urban arterial streets.

Some typical values will be suggested as default values in a later section. However, the distribution of truck accident types on these highways should also be determined in order to make reliable estimates of the probability of a release given an accident. Likewise, truck accident rates by type of truck, type of material, type of highway segment, and corresponding release rates would be beneficial if they were from statistically valid data and could be matched with corresponding exposure data.

Accident rates for all types of trucks combined should be estimated in preference to general (all-vehicle) accident rates because they more closely approximate the accident probabilities of hazmat-carrying trucks. On the other hand, no attempt should be made to determine default accident rates for hazmat-carrying trucks as a group or for specific truck types (e.g., tractor-trailer combination trucks) unless the State also obtains adequate, corresponding exposure data (which is usually unavailable) needed to determine the accident rates for these subclasses of trucks. The implicit assumption that hazmat-carrying truck accident rates are equal to general truck accident rates should be clearly recognized as an assumption; ideally, a State would develop its own exposure data by truck subclass to match subclass accident rates. Further, if a State developed a data base of statistically adequate size (both accident and corresponding exposure data) by highway type, by segment type within each highway type, by truck type, and by hazmat type, it would lead to a much more rigorous analysis. If a State feels such a detailed, rigorous risk analysis is important, it must institute a program to obtain adequate data at whatever level of highway system the risk analysis is to be done--system-wide, specific route, specific segment, etc. As explained below, to develop statistically adequate data, statistically significant samples must be used in all cases, particularly when developing site-specific rates.

If a State does not have statistically adequate system, route or segment-specific data, and does not wish to develop such data, default truck accident rates should be determined from a broadly based sample on highways using relatively current accident data. Default accident rates should be determined through analysis of data for the State primary highway systems for a minimum of two, and preferably three, States. This data could be obtained through cooperative agreements with the State highway agencies. The method anticipated for determining the default truck accident rates will require the following data to be available in computerized form for individual highway segments:

- Highway and area type (see previous list) (could be broken down into special segments within highway types, e.g., ramps, elevated viaducts, curves, dips, hills, etc., if proper statistical samples are used).
- Length of segment.
- Average daily traffic volume.
- Percent trucks (could be further refined by data on hazmat truck, truck type, hazmat material type, and quantity).
- Distribution of truck accident types (e.g., overturning on down ramps, single vehicle run-off-road, single vehicle hitting objects, etc.).
- Number of truck accidents.

If the highway and area type could be further broken down by segment type, and proper statistical analysis of the data was made, then data would be available to better evaluate specific protective systems on specific segments.

Many States have developed computerized highway inventory and accident records systems that could provide this data. It must be emphasized that the State needs to decide whether it wants to expand the resources necessary to develop good hazardous materials accident/incident and exposure data. Only then will good risk assessment follow. The final report of a recent FHWA study includes a section of detailed procedures for States to develop truck accident rates and release probabilities and provides an example for users to follow.(3) This example should be studied.

It is emphasized here that users should be cautioned against using truck accident data for specific route segments unless the segment is long enough and/or enough years of accident data are included so the accident history is large enough to be meaningful. Since accident occurrence is a random variable, accident data cannot be assumed to indicate true differences in risk between segments unless a statistical test indicates that these differences are statistically significant. A simple Chi-square test can be employed to determine whether the actual accident frequency for a specific unit is different enough than the expected accident frequency to warrant replacement of the default truck accident rates with specific rates based on accident histories. Data can be aggregated statewide or multistate for short sections or specific elements such as ramps, bridges, etc.; however, care must be exercised. The analyst should, ideally, have expertise in statistics. (A discussion of proper procedures will follow this section in section 4, Revised Guidelines Recommended for Use.) Unless proper statistical procedures are understood and followed, it is recommended that system-wide, average accident rates or default rates be used in preference to site-specific data. The general rule is to use the best or most robust data available from a statistical standpoint.

d. Impact distances: The impact distances in table 12 of this report should be revised based on the latest available data on evacuation distances for general classes of hazardous materials. The evacuation distances can be based on the maximum evacuation distances for any specific material within a given class of hazardous materials shown in the 1987 Department of Transportation Emergency Response Guidebook and in any subsequent recent research an alternative would be to check with the State emergency response organizations (see appendix C).[5]

e. Population exposed: The procedures in the 1980 routing guide for determining the population exposed to hazmat releases along a particular route segment should be retained. However, the population exposure should be reformulated to avoid double counting the effect of route segment length. The population risk should be calculated as shown below:

$$RPOP_i = P(R)_i \times (POP_i/L_i) \tag{6}$$

The POP_i/L_i term in equation (6) represents the linear population density along the route segment in question.

f. Property exposed: The procedures in the 1980 routing guide for determining property exposed to hazmat releases along a particular route segment should be retained. However, the property exposure should be reformulated to avoid double counting the effect of route segment length, as described in a later section of this report. The property damage risk should be calculated as shown below:

$$RPD_i = P(A)_i \times (PV_i/L_i) \tag{7}$$

In equation (7), the term PV_i/L_i represents the average value of property per mile along the route segment.

g. Property default values: The 1980 Routing Guide should provide a table of representative values of property value per unit length for a range of land uses including, as a minimum, the five types of land use addressed in the FHWA Guide:

- High-density residential.
- Medium-density residential.
- Low-density residential.
- Commercial.
- Industrial.

A State may find it desirable to expand this list to include additional land use types as follows:

- High-density residential.
- Medium-density residential.
- Commercial--office.
- Commercial--retail.
- Industrial.
- Institutional.
- Agricultural.
- Open land.

h. Release/incident probabilities: The 1980 routing guide relies only on accident probabilities; however, we are really concerned with incident probabilities. An accident in itself may not lead to an incident, defined as the release of hazmat with or without a traffic accident. Potentially catastrophic consequences are actually the result of release. The probability of release varies and is not equally likely in all accidents, which is the inherent assumption if one uses only accident probabilities. Thus, the probability of a release should be considered. These rates can be developed if adequate records of releases are kept. Records of quantity released should also be kept.

i. Impact distances: Finally, there is also a need to develop some impact distances for specific materials for site-specific highway segments, and environmental conditions; for example, distance from a spill for cut-sections, on-street heavier than air (applicable to elevated sections) and on-street lighter than air scenarios. This kind of material data and site-specific data are needed to properly analyze consequences for a specific scenario that takes into account highway segment type, material, and environmental conditions.

A summary of distances given in the 1980 Hazardous Materials Emergency Response Guidebook may be found in appendix C.[5] An example of more sophisticated models to determine impact or evacuation distances of airborne, toxic materials is found in appendixes D and E. It is recommended that State highway personnel consult with State or regional Environmental Protection Agency experts on hazmat response.

j. Key to model improvement: It cannot be emphasized enough that the key to the vigor and detail available as output from risk model application is data availability. For protective systems analysis, users are encouraged to develop their own default values for facility-segment type, e.g., freeway ramp, elevated or depressed freeway, bridge, etc., as well highway type, area, region, etc. These should be consistent with the elements shown in tables 4 and 5 or a similar list developed by a particular State after determining which elements are of importance to the State, in a manner that data can be accumulated area-wide or system-wide. Proper statistical procedures must be used, as described in a following section. Where protective systems are incorporated, both before and after data of this type are desirable. This will also allow evaluation of protective system risk-effectiveness and cost-effectiveness over the years. At this point in time (1989) this will have to be based on judgement.

4. Revised guidelines recommended for use

The basis for this section is the recent FHWA final report, that recommends revised guidelines.[2] The author of this manual believes the recommended revisions are appropriate to the analysis of protective system use.

This section sets forth the revised FHWA risk assessment model developed for evaluation of alternative hazmat transportation routes incorporating several of the modifications discussed above. It is recommended that these procedures be used in the analysis of protective system use. When better and more detailed data are available, then better and more detailed results will be available with this model. The format of the procedures follows that of the summary of the original FHWA guidelines presented above, including a discussion of changes that should be made to each of the three steps in the procedure.

a. Determine accident probability: The probability of a hazmat accident should be computed with the following equation, which replaces equation (1) (equation (2) in the original FHWA procedure):

$$P(R)_i = TAR_i \times P(R|A)_i \times L_i \qquad (8)$$

where: $P(R)_i$ = probability of an accident involving a hazmat release for route segment i

TAR_i = truck accident rate (accidents per veh-mi) for route segment i

$P(R|A)_i$ = probability of a hazmat release given an accident involving a hazmat-carrying truck for route segment i

L_i = length (mi) of route segment i

The first term in equation (8) is the truck accident rate per veh-mi (TAR_i) for the route segment in question. Table 13 presents default values of truck accident rate for different highway classes that can be used in equation (8). The table is based on combined data for the entire State highway systems of California, Illinois, and Michigan. However, users who wish to use default values, are encouraged to develop default values based on average data for their own jurisdictions using the procedure given in appendix A of this manual.

The second term in equation (8) is the probability of release given an accident involving a hazmat-carrying truck for the route segment in question. Table 13 also includes default estimates of this quantity by highway class, based on truck accident type distributions for the entire State highway systems of California, Illinois, and Michigan and nationwide data on release probabilities by accident type from the FHWA motor carrier accident reports. Appendix A also contains procedures for any State to determine the probability of release given an accident.

Table 13. Default truck accident rates and release probability for use in hazmat routing analyses.[2]

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

The third term in equation (8) is the length of the route segment (L_i). Length is considered to be the determination of accident probability because it is a direct measure of the exposure of vehicles to the risk of accidents. For example, if one alternative route is twice as long as another, a vehicle traveling the longer route has twice the risk of an accident due to the difference in length alone, even if the accident rates of the two segments are same.

b. Statistical procedure for testing data: In most cases, the truck accident rates shown in table 13 or, better yet, average values for the user's own jurisdiction should be used as the value of TAR_i in equation (8). However, a simple statistical procedure, based on the Chi-squared test, should be used to determine whether the actual accident frequency for a particular route segment is enough larger or smaller than the expected accident frequency to warrant replacement of the default truck accident rates by site-specific rates based on accident histories. This procedure is employed as follows:

Step 1. Obtain truck accident data for as long a time period as possible for a particular highway segment. This observed accident frequency is referred to as A_o.

Step 2. Compute the expected truck accident frequency for that same time period using system-wide default accident rates such as those presented in table 13. The expected truck accident frequency can be computed as:

$$A_e = TAR \times TADT \times L \times 365 \times N \qquad (9)$$

where: A_e = expected truck accident frequency;

TAR = expected truck accident rate (accidents per veh-mi) based on table 13 or State data;

TADT = average daily truck traffic (veh/day);

L = length of highway segment (mi); and

N = duration of study period (yr).

If $A_e \geq 5$, then use the Chi-squared procedure given in step 3. If $A_e < 5$, then the accident sample size is too small to use the Chi-squared procedure, and an alternative procedure in step 3 based on the Poisson distribution should be used.

Step 3. If $A_e \geq 5$, compare the expected and observed accident frequencies by computing the Chi-squared statistic:

$$x^2 = \frac{(A_e - A_o)^2}{A_e} \qquad (10)$$

where: x^2 = Chi-squared statistics;

A_e = expected truck accident frequency; and

A_o = observed truck accident frequency.

If $x^2 \leq 4$, then the expected and observed accident frequencies do not differ significantly at the 5 percent significance level. Therefore, the system-wide default accident rate should be preferred to site-specific accident data.

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

Step 3b. An alternative procedure based on the Poisson distribution is used whenever $A_e < 5$, because the Chi-squared test is not applicable to this small accident sample size. Table 14 shows critical values from the Poisson distribution for testing the significance of difference from the expected accident frequency:

If A_o exceeds the critical value given above for the known value of A_e, then the expected and observed accident frequencies differ significantly. In this case, the system-wide default accident rate should be replaced by the site-specific accident rate. If $A_e < 5$, it is recommended that the default accident rate should never be decreased, because the available sample size is rarely adequate to indicate a true accident rate lower than the expected value.

Example. For example, suppose a 1.8-mi (2.9 km) section of rural freeway with a truck volume of 5,000 trucks per day has experienced 10 truck accidents in the last 3 years (i.e., $A_o = 10$). The expected truck accident rate for a rural freeway, based on table 13, is 0.64 accidents per million veh-mi (0.40

Table 14. Critical Poisson distribution values.[(2)1]

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

[1]Any basic statistics book may be consulted for these values and discussion of the Chi squared statistic.

accidents per million veh-km). The expected accident frequency of this freeway segment for a 3-year period is:

$$A_e = 0.64 \times 10^{-6} \times 5{,}000 \times 1.8 \times 365 \times 3 = 6.3 \text{ accidents}$$

The Chi-squared statistic is calculated as:

$$x^2 = \frac{(6.3 - 10)^2}{6.3} = 2.17 \qquad (11)$$

Since 2.17 < 4, the observed accident frequency for the segment is not significantly different from the expected accident frequency. Therefore, the expected accident experience, rather than the observed accident experience, should be used in a hazmat risk assessment. In this case, the observed accident frequency would have to be greater than 12 truck accidents in a 3-year period to justify use of a truck accident rate higher than the expected value. If, for example, this freeway segment has actually experienced 15 truck accidents in the last 3 years, then the appropriate truck accident rate for use in hazmat risk assessment would be:

$$TAR = \frac{15 \times 10}{5{,}000 \times 365 \times 3 \times 1.8} = 1.52 \text{ accidents per million vehicle-miles} \quad (12)$$

Users are encouraged to use proper statistical tests to develop their own default truck accident rates based on system-wide data for their own jurisdiction. Accident rates based on statistically valid system-wide accident data for a specific State or municipality are likely to be more reliable than default rates based on data from other jurisdictions. For more detailed breakdowns, a statistician should be consulted.

c. Determine accident consequences: The risk assessment model considers two types of consequences from an accident involving a release of hazardous materials. These are personal injury consequences and property damage consequences. Both of these consequences are compared between routes based on the population potentially exposed and the value of the property potentially exposed to a hazmat release.

The model assumes that the personal injury consequences of a hazmat release are proportional to the population potentially exposed to the release. The population potentially exposed to a release may be estimated on the basis of residential population, employment, motorists, or a combination of the three. The application of the model to residential populations is illustated in the guide. The four steps in evaluation of exposed residential population are:

- Delineate the potential impact zone on census tract maps that include the area around the route segment in question.
- Determine what proportion of each census track is located within the impact zone.
- Multiply the census tract population by the proportion of the census tract within the impact zone.
- Sum the exposed populations for all census tracts along the route segment.

A similar approach is used for the assessment of property damage consequences, which is considered to be an optional component of the risk assessment model. The property damage consequences of a hazmat release are assumed to be proportional to the value of the property adjacent to the route segment in question. (The model considers only property adjacent to the roadway, not property within the entire impact zone for population risks defined above.) The steps in the assessment of the value of property exposed to a hazmat release are as follows:

- Determine lineal frontage for each land-use type.
- Estimate dollar value per linear foot for each land-use type.
- Multiply lineal frontage of each land-use type by the associated value per lineal foot, and sum across all land-use types for each route segment.
- Add the value of roadway structures owned by the highway agency on the route segment.

A worksheet for assessing the value of property exposed to a hazmat release is also provided in the FHWA guide.

d. Calculated risks: The basic equation for calculating risk as the product of the probability of a hazmat accident and the population or property damage consequences of an accident is unchanged from the original FHWA model. Thus, in general,

$$\text{Risk} = \text{Probability} \times \text{Consequences} \qquad (2)$$

The population risk is computed in the revised FHWA model:

$$RPOP_i = P(R)_i \times (POP_i/L_i) \qquad (6)$$

where: $PROP_i$ = population risk along route segment i; and

POP_i = number of persons with the specified impact zone width exposed to a hazardous materials release along route segment i.

The POP_i/L_i term in equation (6) represents the linear population density along the route segment in question. The property damage risk is computed in the revised FHWA model as:

$$FPD_i = P(A)_i \times (PV_i/L_i) \qquad (7)$$

where: PV_i = total property value along route segment i.

The PV_iL_i term in equation (7) represents the average value of property per mile along the route segment.

The total population risk or total property damage risk for each alternative route is computed by summing all of the individual risks along each route. The risk assessment model does not provide a method for combining or weighting the population and property damage risks for a route, so these risks must be considered separately. It is recommended that they be weighted and combined but the weights given to each must be a decision by the State.

III. INFORMATION ON PROTECTIVE SYSTEMS AVAILABLE FOR COMMON PROBLEMS

A. Introduction on Specific Protective Systems for Hazardous Materials Spills on Highway Systems

1. Philosophy

Preventing movement of vehicles carrying hazardous materials over areas where an accident may have a catastrophic consequences is the simplest way to handle spill problems. This, however, may not always be practical or feasible. The task then is to reduce the risk of potentially catastrophic accidents, or mitigate the consequences, as it is impossible to eliminate all accidents.

This section presents brief sketches of protective systems which may reduce the risk, or probability of an accident, or mitigate the consequences arising from an accident. Most of these have been suggested by State personnel serving as respondents on the project's advisory panel. The published literature has no reference to direct uses of such protective systems in the highway environment except for containment basins originally designed to mitigate pollution from general highway runoff, and high-strength bridge rail that could have direct application by containing hazmat tank trucks within the highway system. Design details are left to the States and/or manufacturers, suppliers and consultants with expertise in the various specific areas. The material in this manual should guide the State to a decision on the practicability of designing a specific system.

In the following sections, the aim is to discuss the protective systems helpful in prevention of accidents or mitigating hazmat incidents that can lead to catastrophic consequences. These systems followed from the ranked scenarios and protective system development described in previous chapters.

2. Scope

A hazmat spill problem would involve notification of safety authorities, identification of the material, containment of the spill, and clean up. However, preventive and/or mitigation measures with protective systems would involve various physical improvements, introduced here and detailed in the following chapters.

3. <u>Scenarios and solution types</u>

To handle an emergency from trapped motorists being exposed to poisonous, toxic, flammable, or explosive materials in a cut section or low area, the following measures may be helpful:

- Traversable medians could be constructed so traffic could be redirected.
- Frequent crossovers and means of escape from depressed freeways, tunnels, etc., could be provided.
- Easy access could be provided for emergency responders.

To mitigate the effects of poisonous or explosive materials entering underground transit stations or tunnels, some of the measures mentioned below could be effective:

- Vents designed in free-trap style so released gases get trapped in the first section.
- Vents equipped with electronically controlled sealed doors that could be closed in case of a spill.
- Built-in automatic foam generators and sensors.
- Coamings around street-level intake vents with drainage away from vents; for overhead stations, the ability to crash-stop ventilation and provide positive internal air pressure to prevent toxic intrusion.

An emergency arising out of an accident of a vehicle carrying hazardous materials inside a tunnel may be handled in the following ways:

- Provide sprinkler and vent systems.
- Install foam systems at periodic intervals.
- Convey hazmat vehicles through the tunnel by police while closing them off to general traffic.
- Provide emergency exits with heavy doors with quick response.

Accidents of hazmat vehicles on elevated facilities, ramps, bridges or mountainous areas could be catastrophic to people living below or in adjacent buildings. Such accidents must be prevented as far as possible. Practical approaches to take care of such problems could include the following:

a. Installing longitudinal traffic barriers or rails capable of sustaining an 80,000-lb (36,320 kg) tank-type truck or tractor-trailers. (On bridges spanning a potable water supply, this type of rail is essential.)

b. Shoulder and slopes should follow good design practice in regard to clear zones to mitigate consequences of truck overturns and rollovers resulting in spills.

c. Closed drainage systems should be considered.

d. Runways or escape ramps should be considered in vulnerable mountainous areas. These are constructed of materials such as loose gravel trucks slowly sink into, thus slowing them to a controlled stop.

e. On roads or sections with catastrophic potential the geometric design should be far greater than minimum standards, the highest standards economically possible should be considered. Wider turning radii, longer acceleration and deceleration ramps, and better maintained roads with non-skid surfaces also reduce accidents.

The interaction of ramp geometry and truck dynamics is covered in a subsequent section. Particular attention should be given to critical locations discussed in that section.

Quick response action by emergency responders reduces consequences; therefore, consideration should be given to:

- A traversable median which could lead the rescue team to the site without any traffic interruption or aid in motorists escaping from the area.
- Ramps designed to facilitate flow of emergency vehicles.

Protection of water supply sources from accidental hazmat spills can be carried out in several ways:

- Storm water drainage from bridges and roadways should not be allowed to flow directly to the water body; instead, it can be directed to a retention basin where contamination can separated from drainage in the basin before it flows to the water body. Examples of some common basins are discussed in a later section.
- Retention basins, however, serve no purpose when the compound is water soluble. In such case, a closed system with some sort of chemical treatment plant is required prior to the water flow into the main water body. Design of such a treatment plant is beyond the scope of this manual.

4. Summary

Marginal vehicle factors combined with marginal roadway, environmental and human factors often result in accidents. To minimize accidents, future design and maintenance programs will warrant broader shoulders, flatter slopes, longitudinal center barriers, longer acceleration and deceleration ramps, higher frictional surfaces, sufficient traffic control signs and devices, etc. To mitigate the consequences of a spill, highway designers must consider traversable medians, shoulders and other such modifications for easier access to incidents, crossovers and other escape routes, barriers capable of restraining 80,000-lb (36,320 kg) tank trucks, retention and holding basins to contain spills, communication systems for prompt notification of authorities, and response systems such as water sprinklers, foam dispensers, etc., built into or near the highway environment. Automatic monitoring devices to activate warning systems and some mitigating systems need to be further studied.

Several protective systems that show promise of being cost-effective, practical systems are discussed in the following sections of this chapter.

Chapter IV presents information on examples of automatic monitoring and warning devices that could be applicable with additional research and development.

B. High Performance Bridge Rail Systems

1. Introduction

Bridge rails are generally designed to restrain and redirect passenger cars. Collisions of large trucks with such rails, in the past, have resulted in catastrophic accidents. For trucks carrying hazardous materials, a potentially catastrophic occurrence is even more likely. Consequently, highway researchers and designers have shown concern for reducing the severity of these accidents by studying containment and redirection of large trucks at selected locations. The results of research and information regarding the design of bridge rails to contain and redirect large trucks are available, albeit limited. Thus, there has been an urgency for researchers to design, build, and test bridge rails to contain and redirect large trucks. FHWA has a major testing program underway in this area.[6]

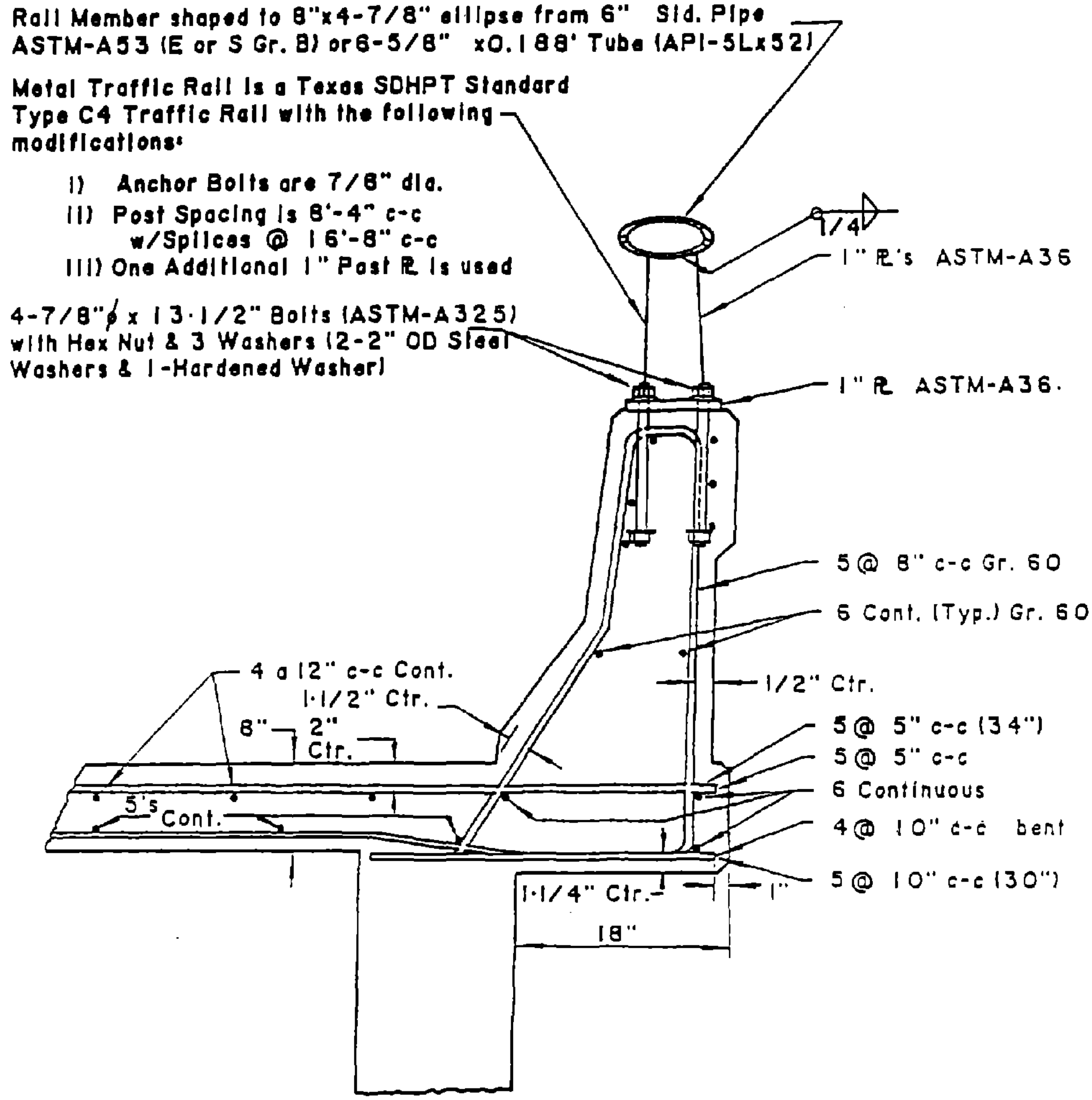
Researchers in Texas have been studying the unique problems of a tank truck's higher center of gravity since 1976, when an ammonia truck went through an upper deck bridge rail on a Houston freeway overpass and overturned and ruptured on the freeway below.[7] Six people were killed, 78 hospitalized, and more than 100 were injured. In all, 184 casualties resulted, mostly motorists trapped as the resulting toxic cloud spread down the highway.

Research on bridge rail to restrain and redirect buses has been carried out with encouraging results.[8,9,10,11,12] In general, the objective of most of the research on high performance bridge rail systems has been to select an existing bridge rail system, redesign and modify or strengthen it, if needed, to give it the capacity to redirect buses and/or trucks.

Several bridge rails which will restrain and redirect large trucks have been designed recently. A bridge rail was designed, built, and tested to contain and redirect an 80,000-lb (36,320 kg) van type tractor/trailer combination impacting at 15 degrees and 50 mi/h (80.5 km/h). (The design details are based on data presented in references 8 through 13.)

The combination rail selected was a modification of the Texas type T5 traffic rail with a modified Texas type C4 metal traffic rail mounted on top. The modified T5 rail included a concrete safety shaped parapet 32 in (81.3 cm) high. The concrete parapet was thickened to 10.5 in (27 cm) at the top and 20 in (51 cm) at the bottom and contained a large amount of reinforcing steel. This provides both flexibility and strength, thus minimizing cracking of concrete and permanent deflection of rail when impacted by heavy vehicles. To minimize cracking and provide greater strength, the thickness of bridge deck below the concrete parapet was increased. Drawings of the rail are shown in figures 2, 3, and 4.

The concrete parapet was anchored to the bridge deck by #5 stirrups spaced 8 in (20 cm), and contained eight #6 longitudinal bars. The metal rail mounted on top of the modified T5 concrete rail was a standard Texas type C4 metal traffic rail with three modifications. One additional 1-in (2.54 cm) thick steel post plate (ASTM-A36) was used in the first modification, and this resulted in three post plates in each post. The second modification was the use of 7/8-in (2.2 cm) diameter ASTM-A325 bolts in place of standard 3/4-in (1.9 cm) bolts. The third modification was the reduction of the post spacing from 10 ft (3 m) to 8 ft, 4 in (2.5 m). These modifications were made to increase the strength of the metal rail so it could provide greater resistance to overturning by van trailers.



1 in = 25.4 mm
1 ft = 0.305 m

Figure 2. Cross section of the modified T5 bridge rail.[8]

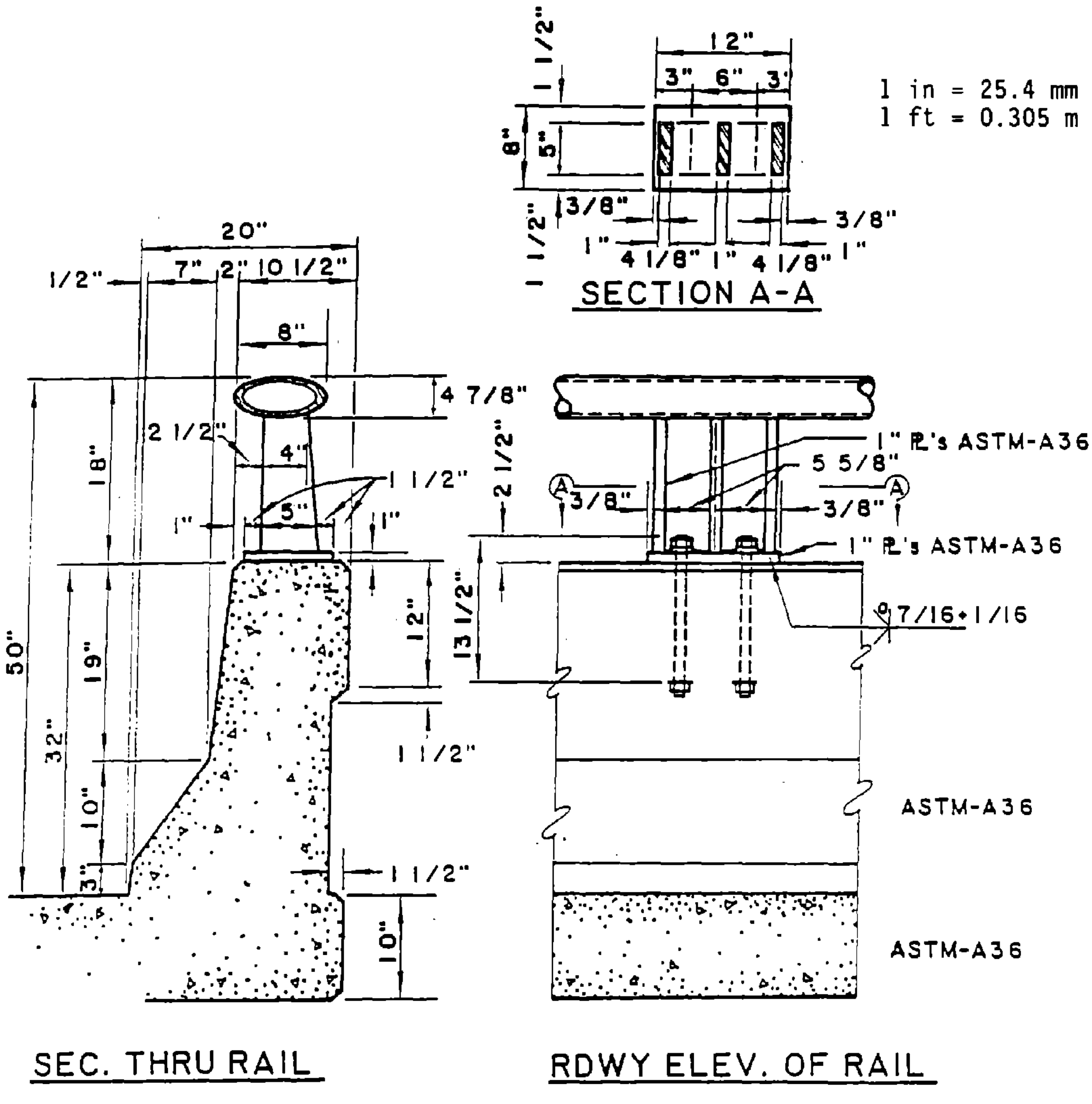
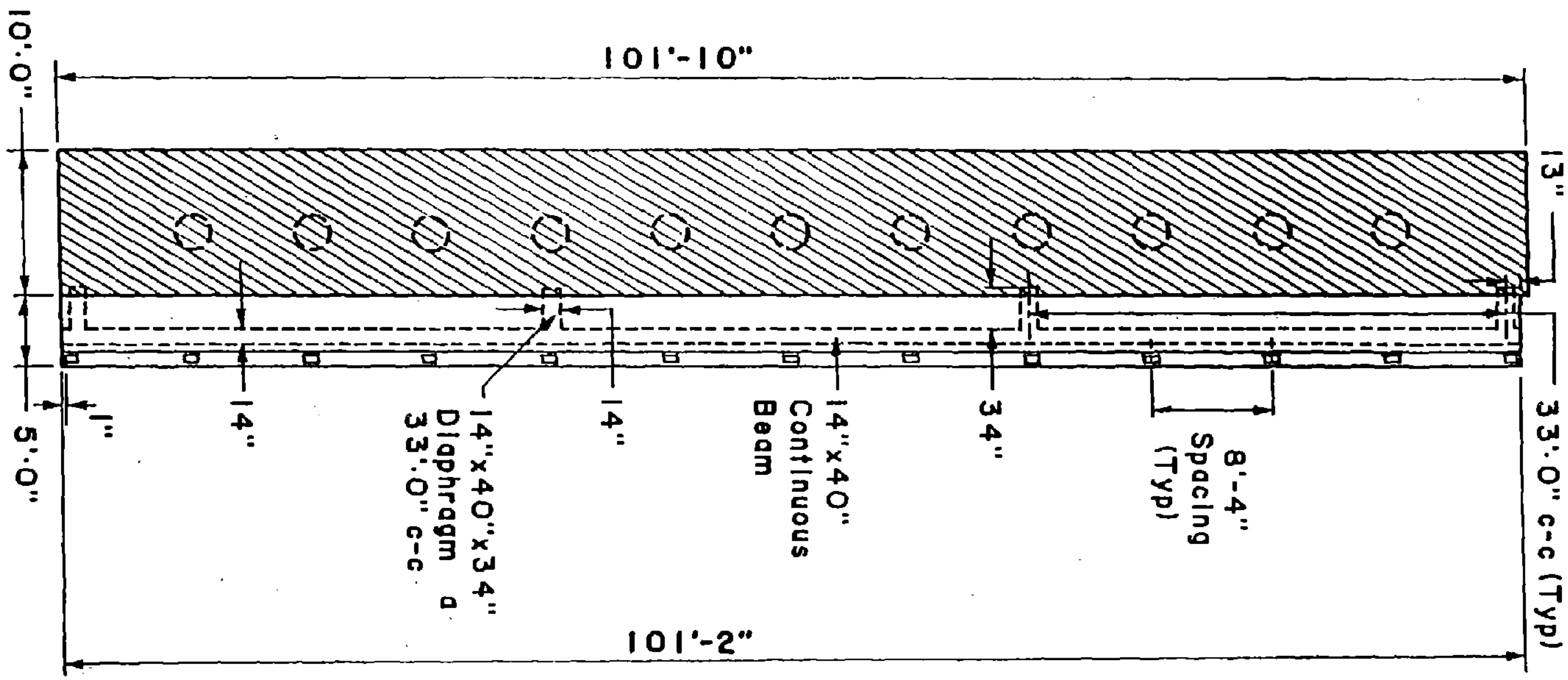


Figure 3. Dimensions and elevation of the modified T5 bridge rail.[8]



PLAN VIEW

1 in = 25.4 mm
1 ft = 0.305 m

(Metal rail member emitted for clarity)

Figure 4. Plan view of the modified T5 bridge rail.[8]

The metal rail was fabricated from 6-in (15 cm) diameter, standard steel pipe (ASTM A53 Grade B) shaped into an 8-in by 4-7/8-in (20 cm by 12.4 cm) ellipse, and welded to the modified post mentioned earlier. In turn, these posts were welded to a base plate made of 1-in (2.54 cm) thick steel plate (ASTM A36). The posts were anchored to the concrete rail by means of four 7/8-in (2.2 cm) diameter by 13.5-in (34.3 cm) long A325 bolts. One 2-in (5.1 cm) diameter steel washer and one hardened steel washer were installed under each bolt nut.

In many ways, the strength of the Texas Standard 7-in (18 cm) thick bridge deck was increased. Except in the cantilever portion of the deck, the dimensions and reinforcement pattern of the standard bridge deck are essentially maintained. The length of cantilever portion was decreased from 30 in (76 cm) to 18 in (46 cm), and the thickness was increased to 10 in (25.4 cm). The size of the upper transverse bars was maintained at #5's, while the standard 5-in (12.7 cm) spacing was decreased to 2.5 in (6.4 cm). The lower transverse reinforcement consisted of an alternating pattern of bent #4's that extended into the lower portion of bridge deck and straight #5's, each at a spacing of 10 in (25.4 cm). The size of the upper and lower longitudinal bars was increased to #6's from #4's and #5's, while the spacing was increased from 12 in (30.5 cm) to 16.5 in (4.9 cm). All reinforcing bars used in the bridge deck reinforcement had a minimum yield strength of 40 psi (275.6 MPa). All of the 28-day compressive strengths were well above the minimum specified strength of 3,600 psi (24.2 MPa).

2. <u>Crash test</u>

At Texas Transportation Institute (TTI), a simulated bridge deck with this rail system was built at proving grounds and tested with a 1981 Kenworth tractor/trailer filled with sandbags to 80,080 lb (36,356 kg).

The FHWA has sponsored a great deal of research on high-strength bridge rail. Several reports are available from the FHWA or TTI which present details of the tests, discussions of the advantages and limitations of the various rail designs and details of the various designs. (Some of the more useful are references 8 through 15).

3. <u>Crash test using CRBRS</u>

The idea of utilizing steel rings as a primary energy-absorbing device for a bridge rail system was conceived by the FHWA Offices of Research and Development. The concept utilizes partial or complete collapse of thick-wall rings to dissipate vehicle impact energy.

Kimball and others developed, designed, and tested a new concept in bridge railing known as Collapsing Ring Bridge Rail System (CRBRS).[14] Even though this system represents an advance in state of the art bridge rail design, it is constructed with conventional materials and barrier elements currently used in highway construction.

This rail system was constructed using ASTM A36 steel plate and structural shape plus ASTM 500 structural tubing. The most important feature of this design was that it could be quickly repaired by maintenance crew with readily available hand tools.

After initial analysis and testing, a bridge railing system which incorporated the collapsing ring concept was designed by FHWA and a vehicle crash test program initiated. Figures 5 through 14 shows details this system. The following notes are applicable to the CRBRS system shown in figure 5:

- Hollow structural tubing shall conform to the requirements of ASTM dsignation a 500 or a 501.
- Bolts and nuts shall conform to the requirements of ASTM designation a 307.
- All materials other than structural tubing and fasteners shall conform to the requirements of ASTM designation a 36.
- No transverse welds permitted in structural tubing sections except as shown on end treatments.
- Welding shall conform to the current requirements of the American Welding Society Structural Welding Code A.W.S.D.I.1.
- Dimensional tolerances not shown or implied are intended to be those consistent with the proper functioning of the part including its apparence and accepted manufacturing practices.

Figures 15 and 16 show the summary of results of two full-scale crash tests of 70,000 lb (27,944 kg) and 40,000 lb (15,968 kg) vehicles, respectively. More details of the collapsing ring bridgerail system design and testing program may be found in references 14 and 15.

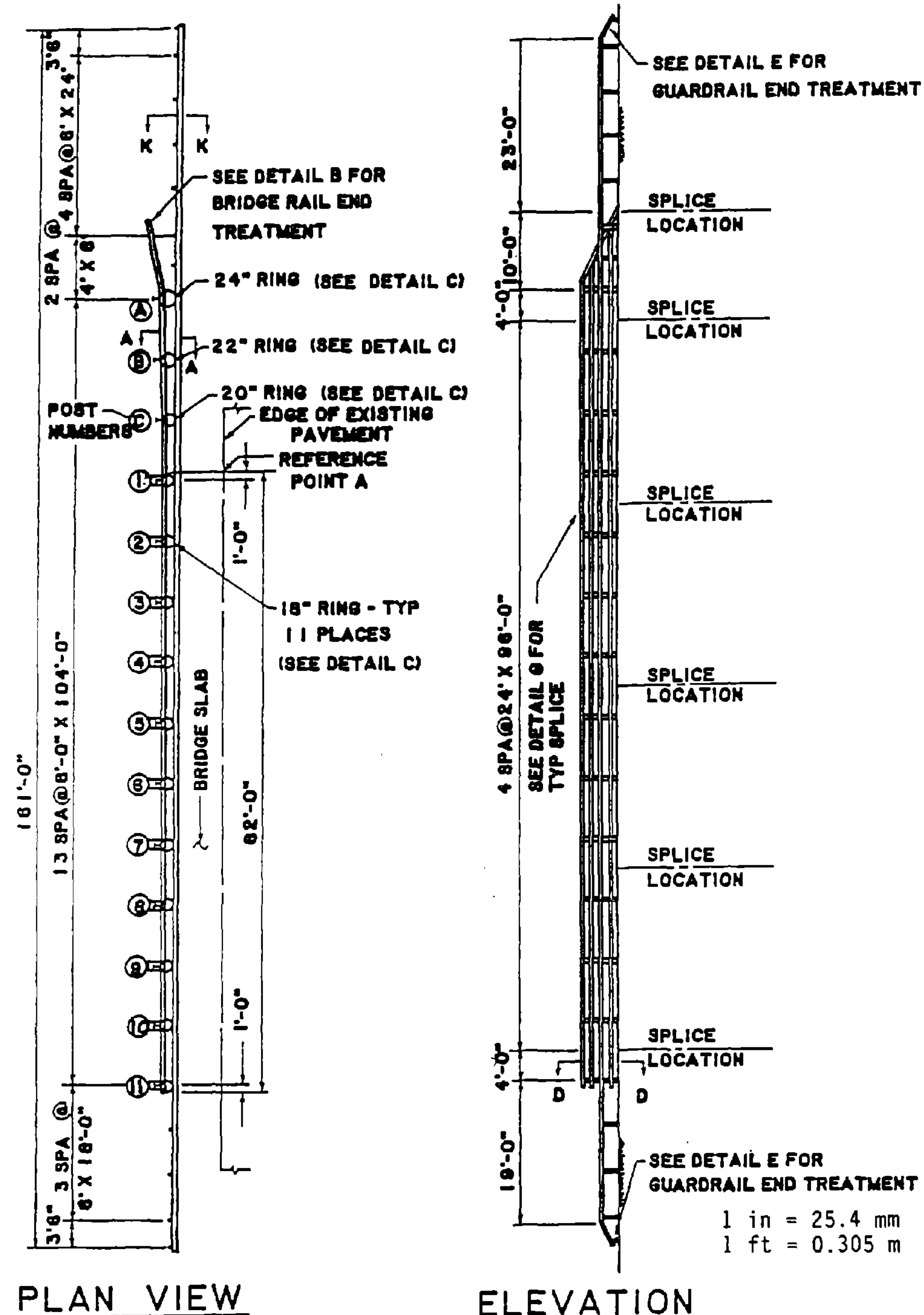


Figure 5. Collapsing ring bridgerail system, plan view and elevation.(14)

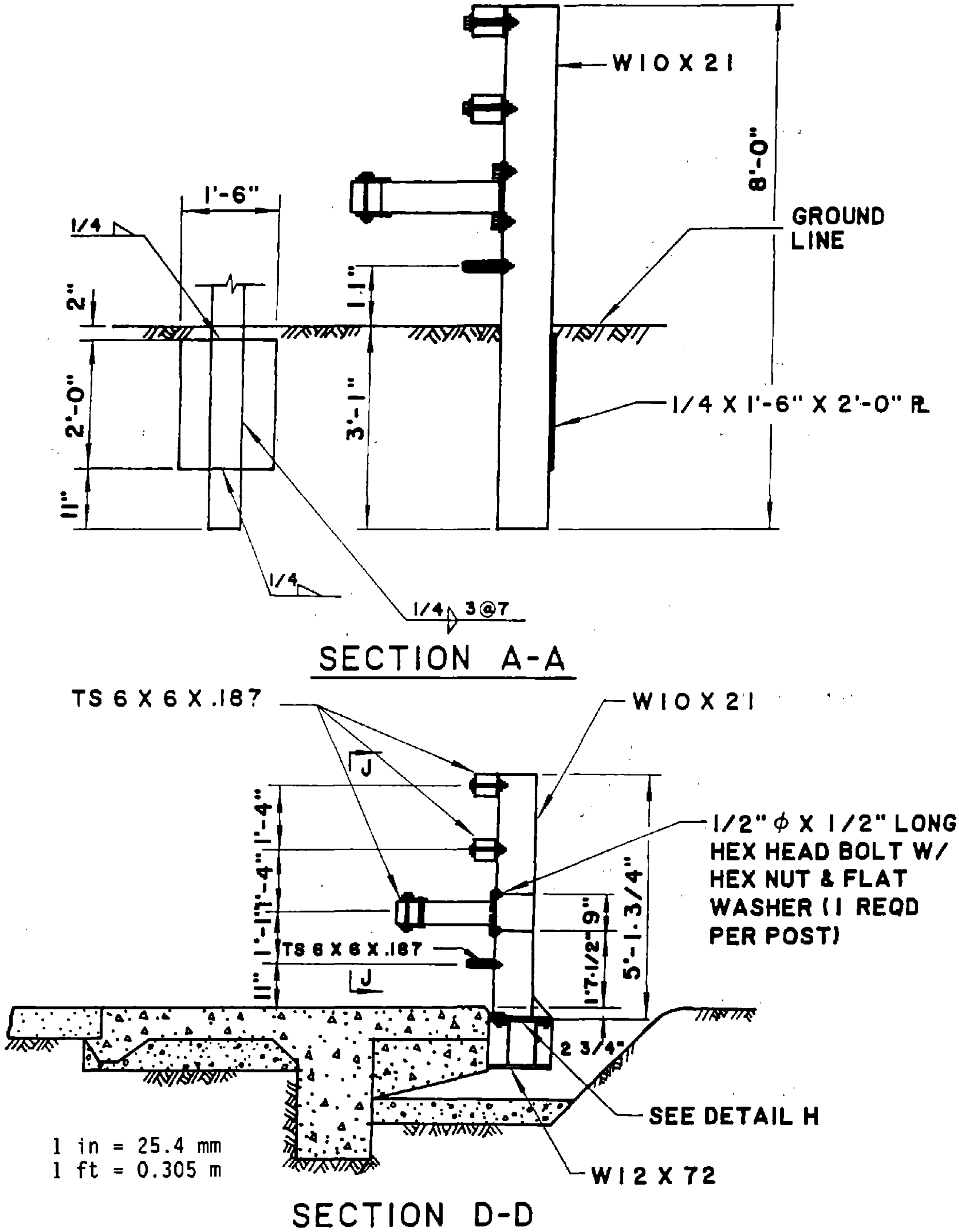
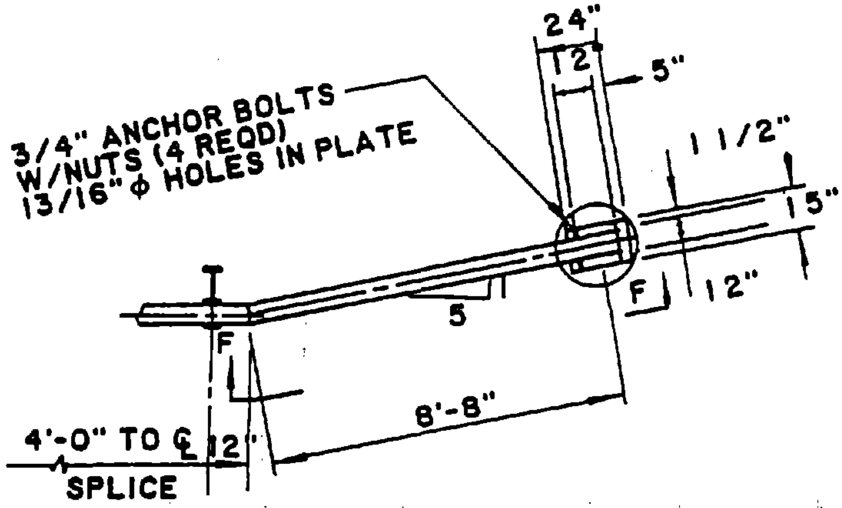
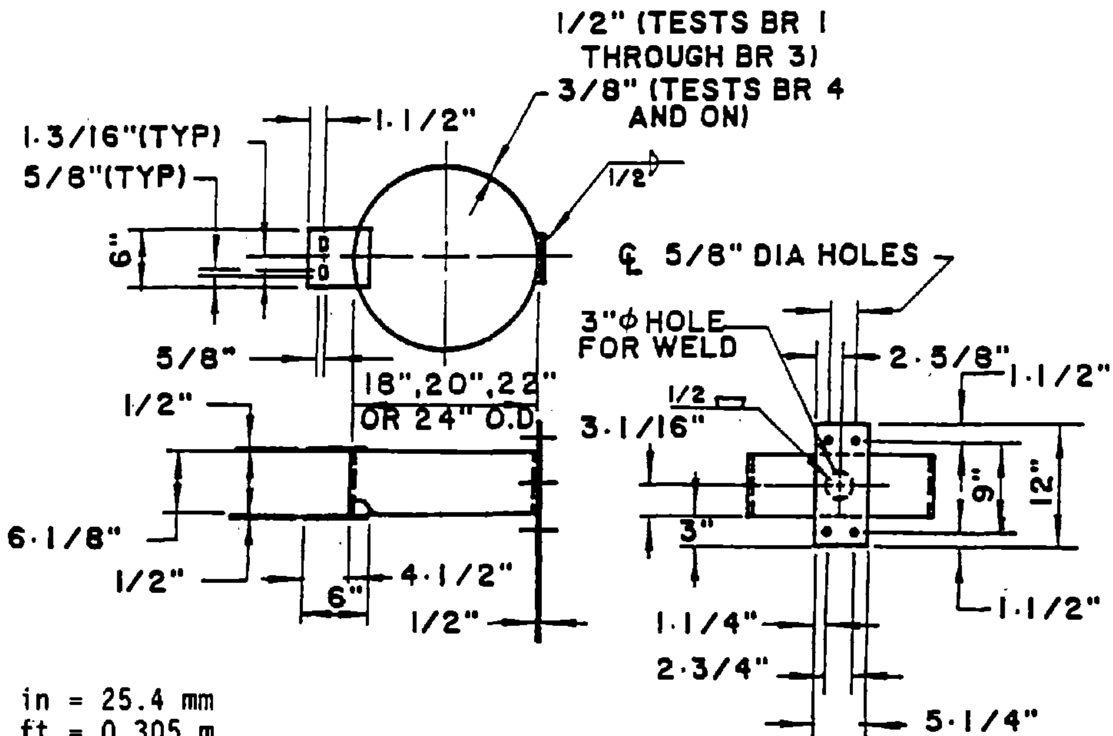


Figure 6. Collapsing ring bridgerail system, section A-A and section D-D.[14]



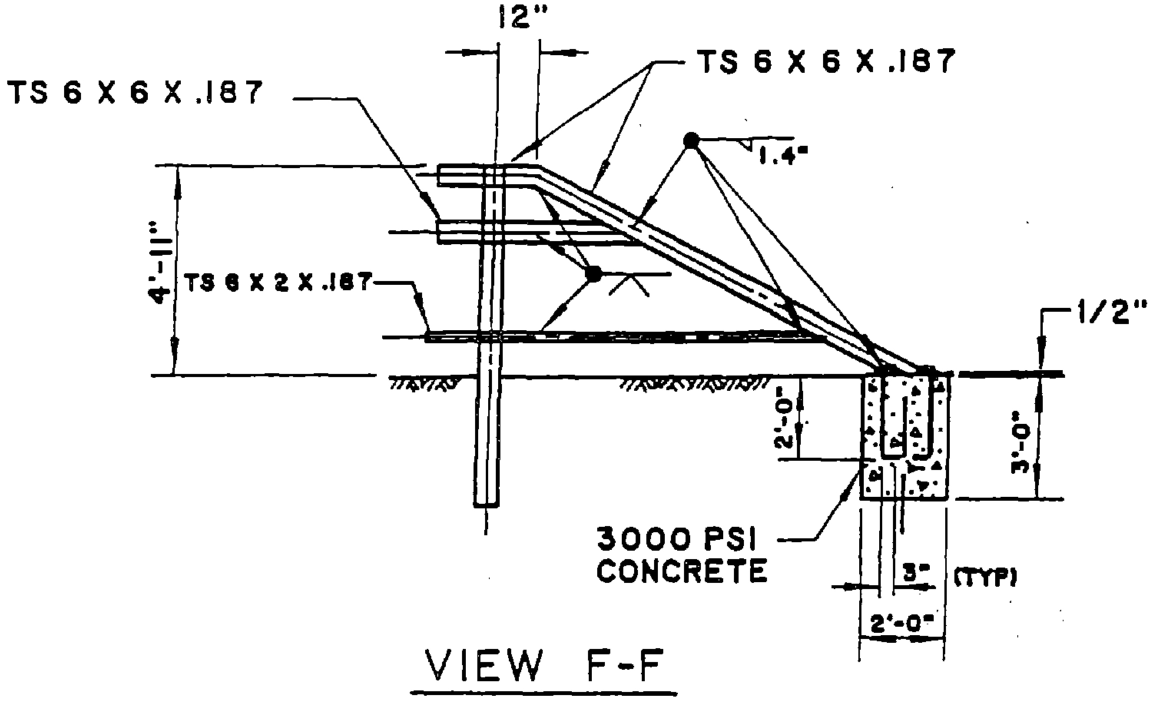
DETAIL B-BRIDGE RAIL END TREATMENT



1 in = 25.4 mm
1 ft = 0.305 m

DETAIL C-RING

Figure 7. Collapsing ring bridgerail system, detail B and detail C.[14]



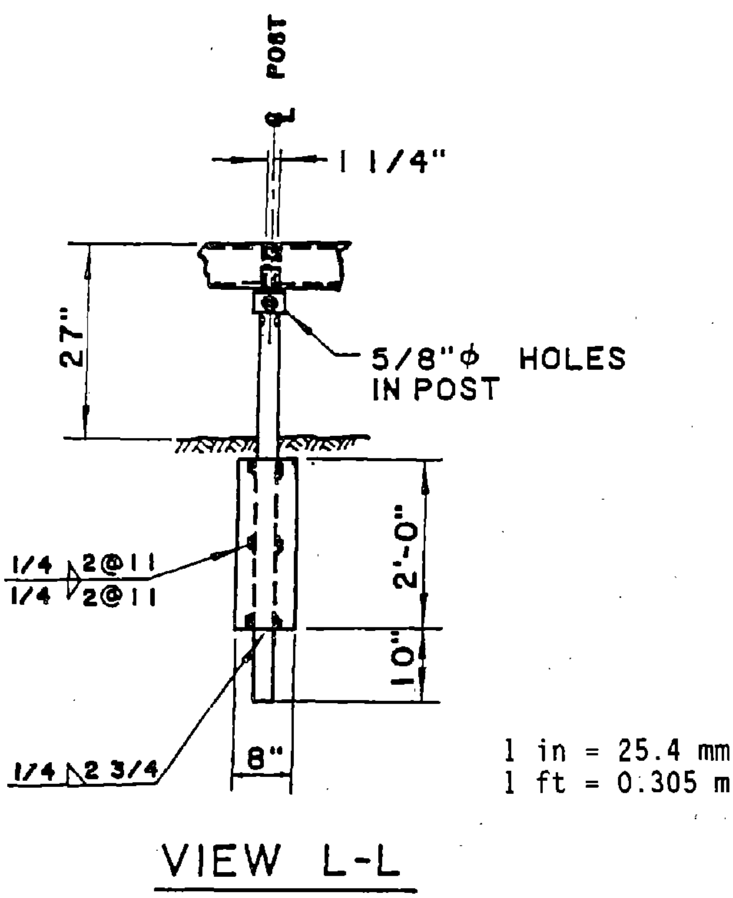
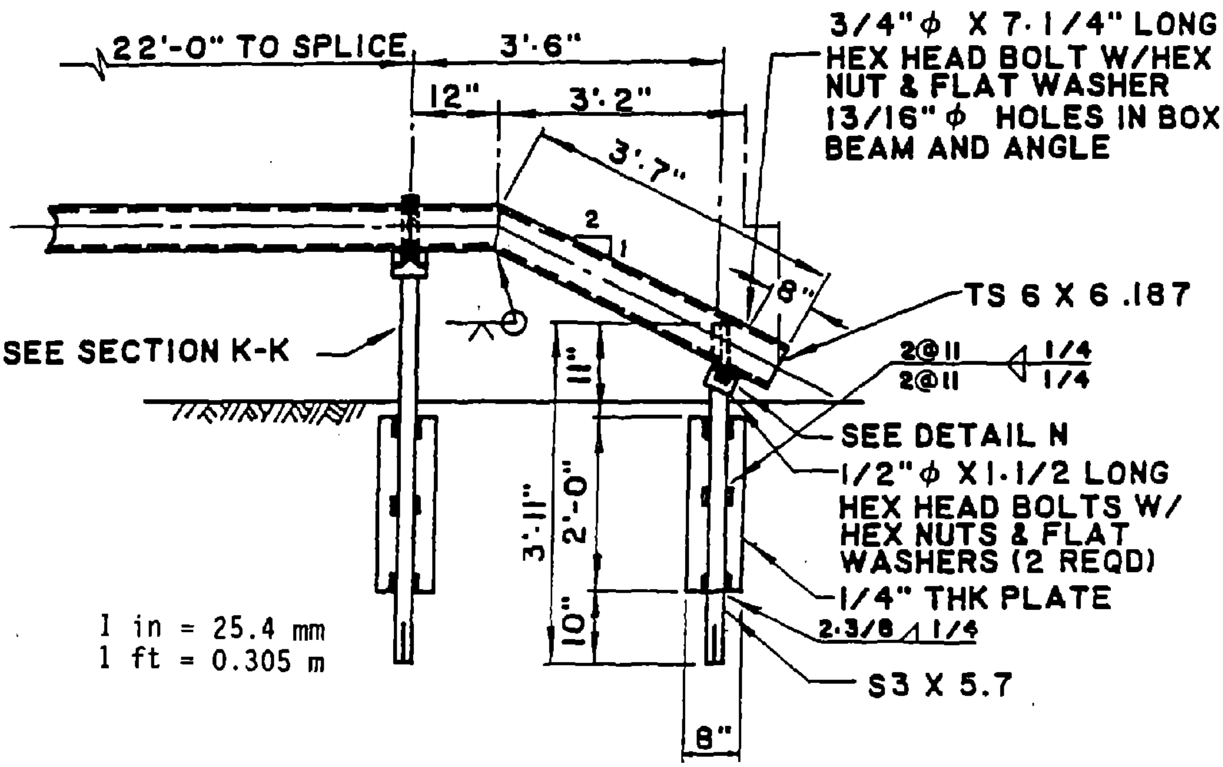


Figure 8. Collapsing ring bridgerail system, view F-F and view L-L. [14]



DETAIL E-GUARDRAIL END TREATMENT

Figure 9. Collapsing ring bridgerail system, detail E.[14]

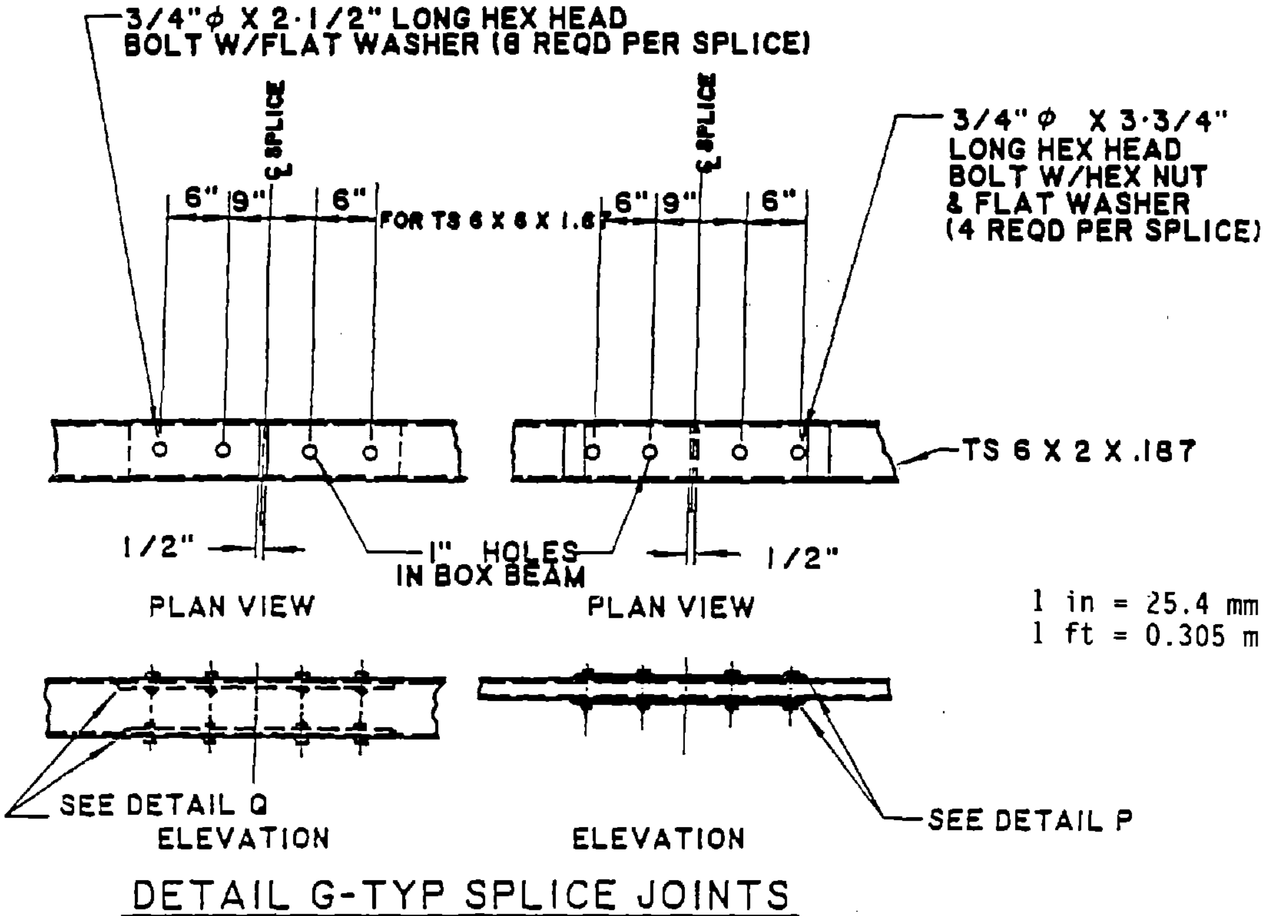
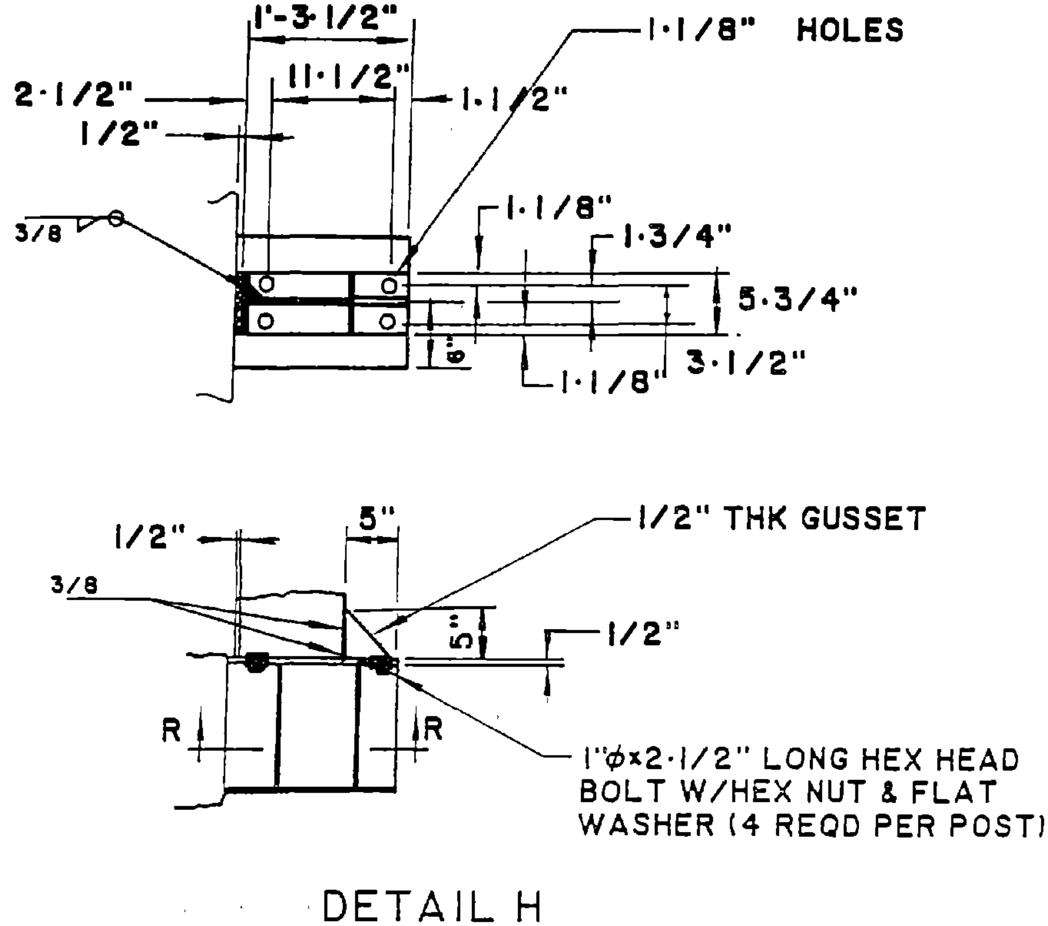
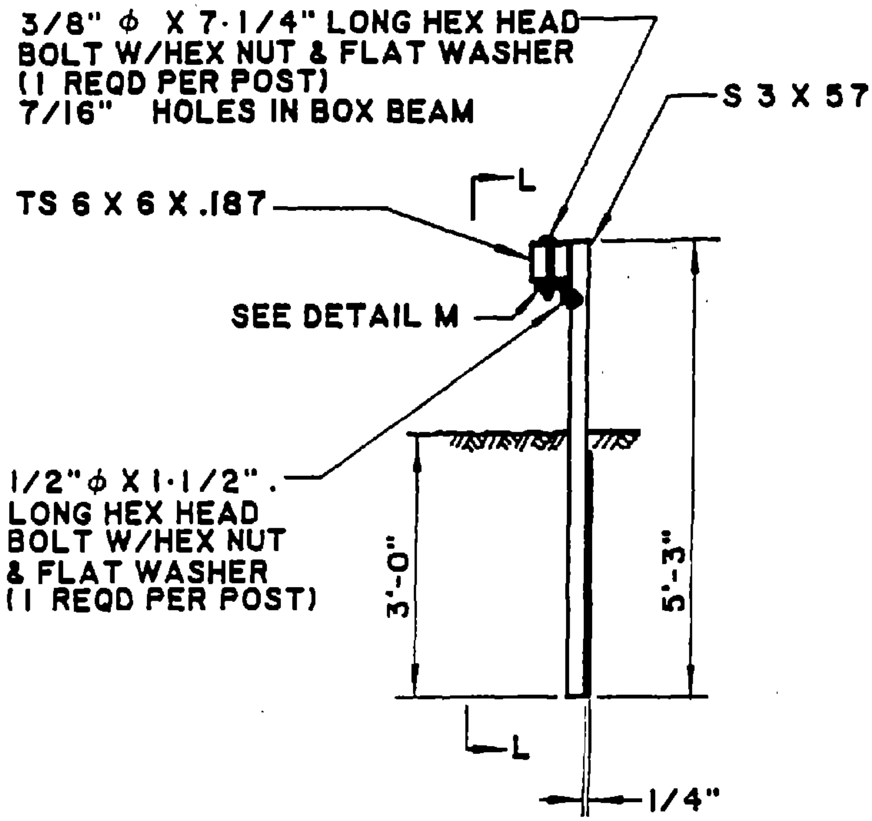


Figure 10. Collapsing ring bridgerail system, detail G.[14]

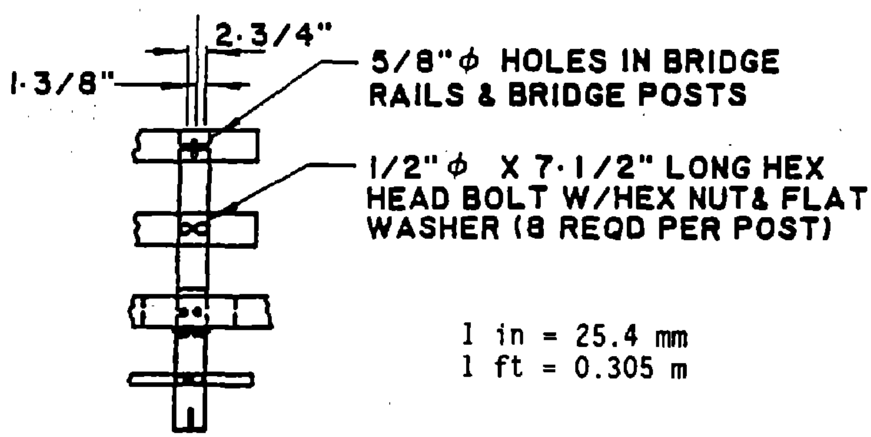


1 in = 25.4 mm
1 ft = 0.305 m

Figure 11. Collapsing ring bridgerail system, detail H.[14]

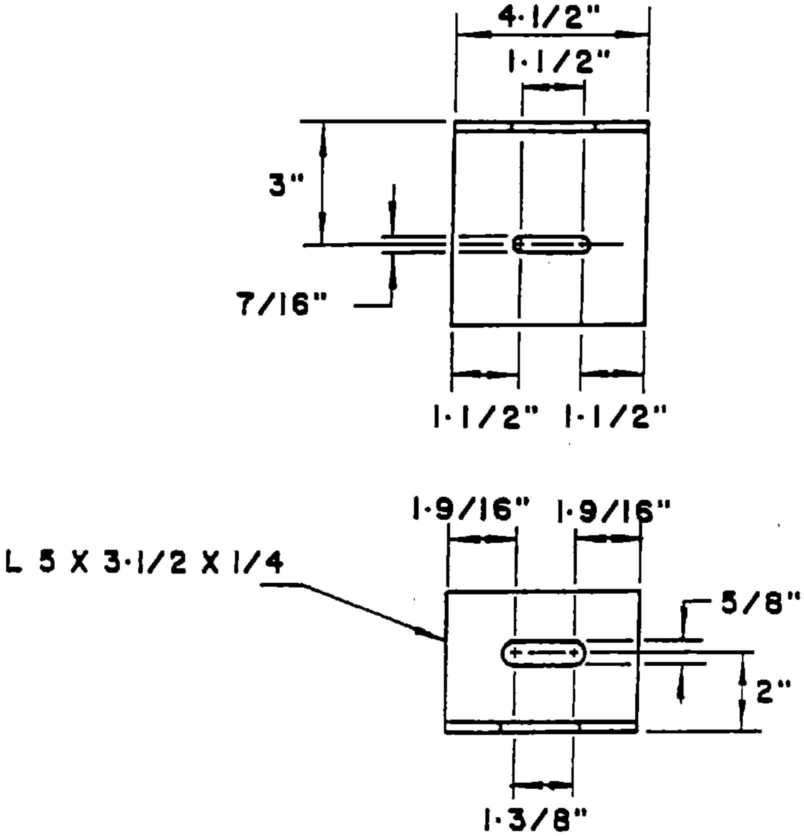


SECTION K-K TYPICAL GUARDRAIL POST

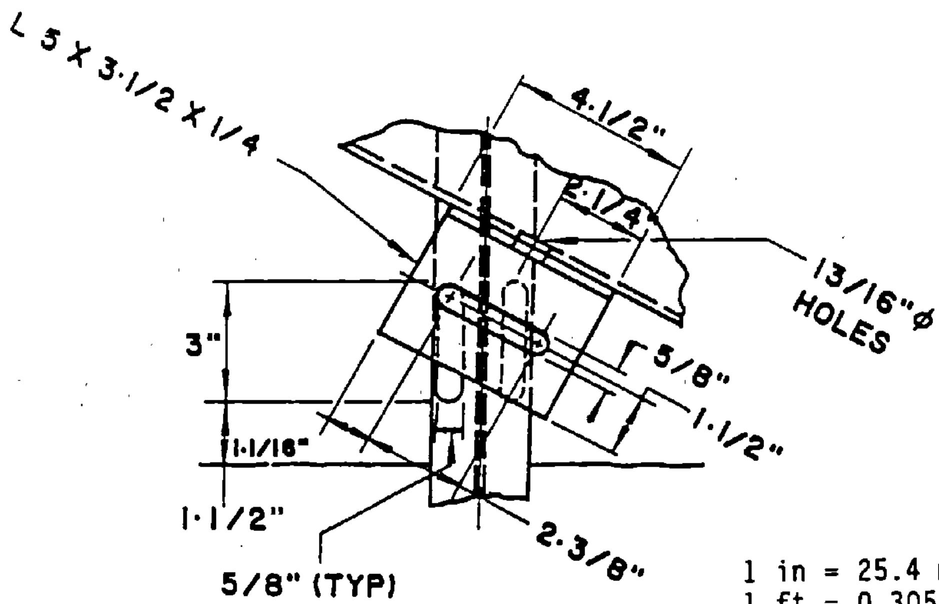


VIEW J-J TYP. BRIDGE POST

Figure 12. Collapsing ring bridgerail system, section K-K and view J-J.[14]



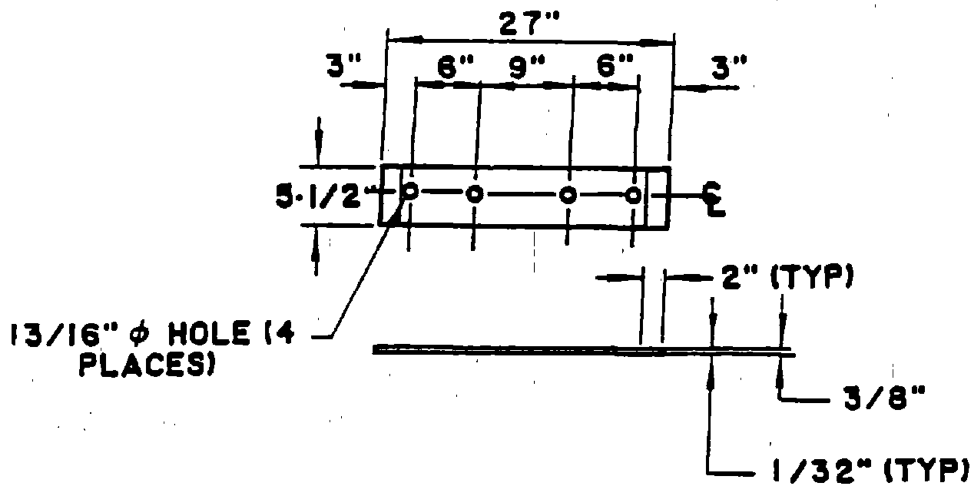
DETAIL M-ANGLE



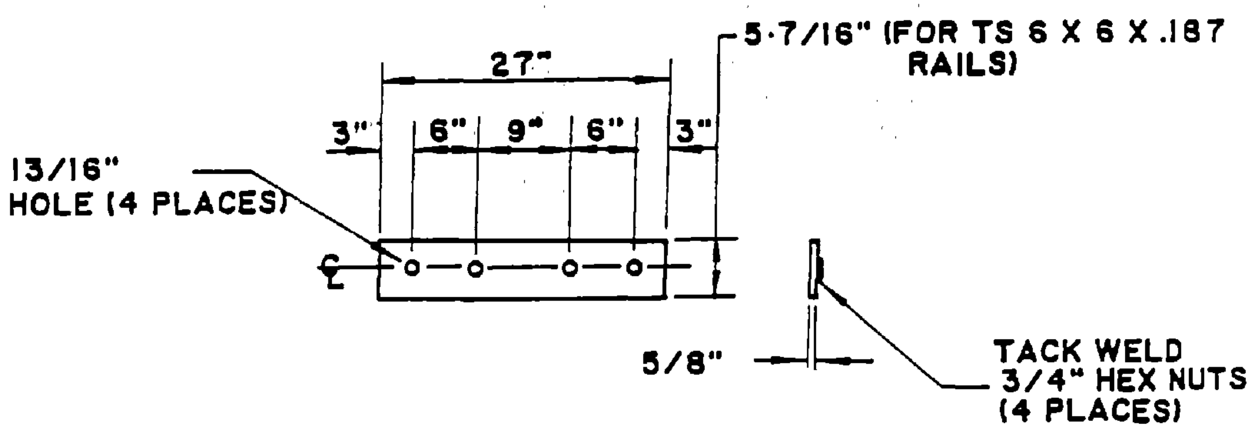
1 in = 25.4 mm
1 ft = 0.305 m

DETAIL N

Figure 13. Collapsing ring bridgerail system, detail M and detail N.[14]



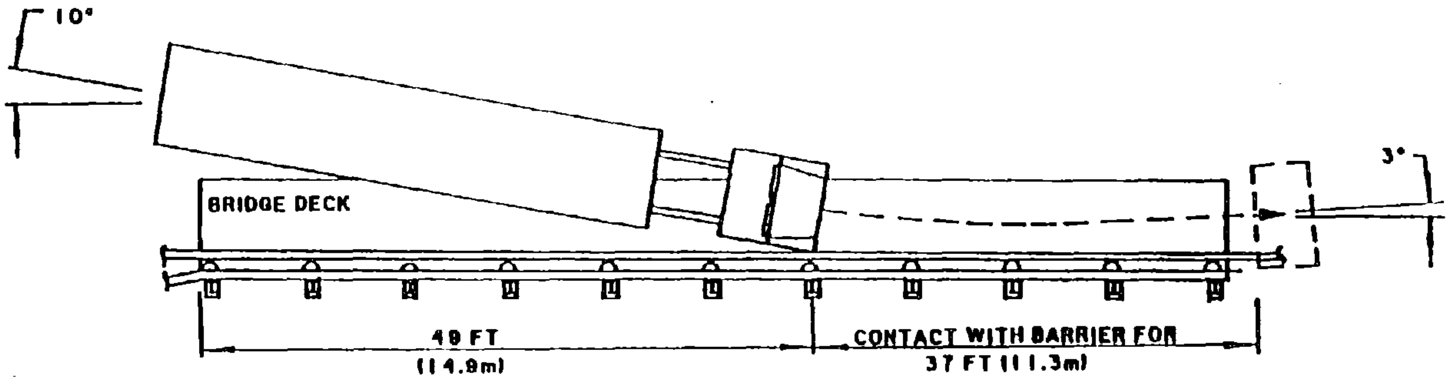
DETAIL P-SPLICE PLATE



DETAIL Q-SPLICE PLATE

1 in = 25.4 mm
1 ft = 0.305 m

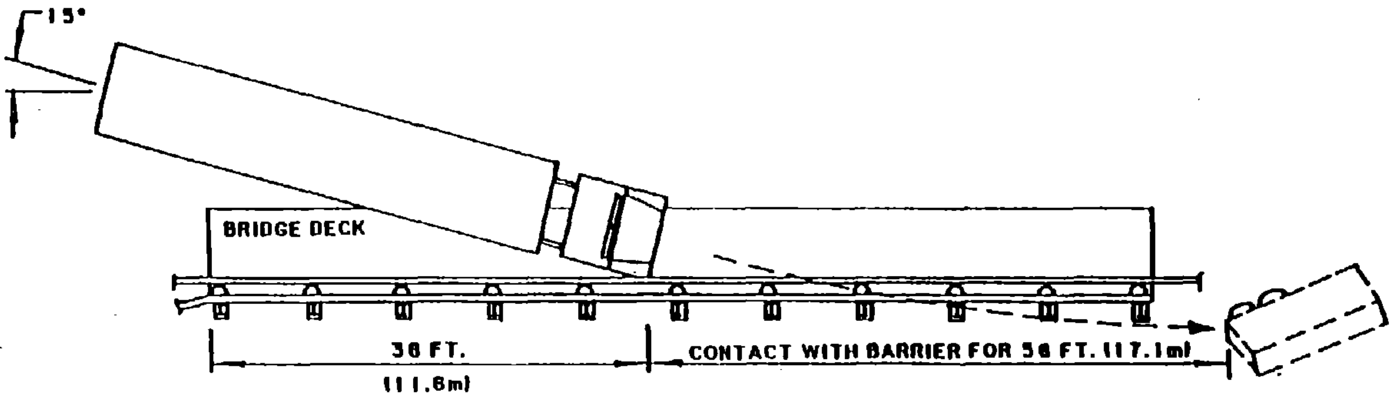
Figure 14. Collapsing ring bridgerail system, detail P and detail Q.[14]



Test No. BR-12
Date 3/19/75
(Barrier Design Identical to Test BR-11)
Pavement Conditions .... Dry
Beam Rail Deflections
Max. Dynamic .... 11.8 in (0.30m)
Max. Permanent .... 9.8 in (0.25m)

Vehicle .... 1964 International Tractor/ 40-ft (12.2m) Trailer
Vehicle Weight .... 70,000 lbs (31,752kg) (w/Instrumentation)
Impact Speed .... 44.4mi/h(19.8m/s)
Impact Angle .... 10 deg
Exit Angle .... 3 deg
Vehicle Accel (max)
Lateral 3.0g
Longitudinal .... -5.0g
Vehicle Rebound Distance .... 10 ft (3.1m)

Figure 15. Summary of results, full-scale crash test BR-12.[14]



Test No. BR-14
Date 4/17/75
(Barrier Design Identical to Test BR-11)
Pavement Conditions .... Dry
Beam Rail Deflection
  Max. Dynamic .... 57.4 in (1.45m)
  Max. Permanent .... 53.4 in (1.36m)

Vehicle ..... 1965 International Tractor/ 40-ft (12.2m) Trailer
Vehicle Weight..40,000 lbs. (18,444kg) (w/instrumentation)
Impact Speed .... 57.0mi/h(25.4m/s)
Impact Angle .... 15.6 deg
Exit Angle .... 3 deg
Vehicle Accel (max 50 ms avg)
  Lateral 7.8g
  Longitudinal .... -1.1g
Vehicle Rebound Distance ... 15 ft (4.6m)

Figure 16. Summary of results, full-scale crash test BR-14.[14]

4. <u>Conclusions: high performance bridge rail systems</u>

The crash tests have shown that:

- A bridge rail can be built with the concrete safety shape on a slightly modified Texas standard bridge deck to contain large van type tractor/trailer trucks. Tests of the rail showed it was successful in containing and redirecting an 80,000-lb (31936 kg) van type tractor/trailer.
- The CRBRS is capable of restraining articulated vehicles weighing up to 70,000 lb (27944 kg) in 45 mi/h (72.5 k/h) 10-degree collisions and 100,000 lb (39920 kg) in 57 mi/h (91.8 k/h) 16-degree impacts.

C. <u>Influence of the Geometric Design of Highway Ramps on the Stability and Control of Heavy-Duty Trucks</u>

1. <u>Introduction</u>

The possibility of a catastrophic, hazardous materials accident/incident on ramps must be given serious attention for several reasons: 1) truck accident rates and hazardous materials incident rates are generally higher at ramp locations; 2) in urban areas, large or sensitive populations could be exposed; and 3) it is a correctable situation. Good geometric design to reduce accidents, with the use of barrier rail to mitigate consequences, may reduce both risk and consequences significantly.

Examining studies and specific cases of truck accidents on ramps helps pinpoint areas that should be given careful attention in considering potential high-risk situations for hazmat spills. If the ramp is in an area where a roll-over or run-off-the-road type accident could cause catastrophic consequences, then design for trucks must be analyzed. Barrier rails should be considered for existing ramps that have been built with marginal geometrics.

Studies have shown accidents experienced by tractor-semitrailers on expressway ramps depend largely on interaction between highway geometrics and vehicle dynamic behavior. One study of 14 individual ramps exhibiting an unusual incidence of service accidents involving these vehicles concluded current practices in ramps design leaves an extremely small margin of safety for control of heavy vehicles.[16]

The study cited above further contends that the current American Association of Highway and Transportation Officials (AASHTO) design manual, <u>A</u>

Policy on Geometric Design of Highways and Streets, makes little or no allowance for the special requirements of trucks.[17] The AASHTO design manual appears to distinctly contrast the specific attention given to truck requirements in other areas of road design, such as climbing lanes, the width of turning roadways, corner radii at intersections, and certain sight distance problems.[17]

Highway ramps are a primary concern. Because of variations in design from one ramp to the next, and because the recommended design policies take no particular note of truck stability and control limits, it appears to be reasonable for the planner/designer to explore the conflicts trucks may encounter in negotiating highway ramps.

The accident record for trucks in general gives an impetus for such concern. For example, the accident file of the Bureau of Motor Carrier Safety (BMCS) for 1980 shows 9 percent of all jackknife accidents and 16.8 percent of all truck roll-overs occur on ramps. A ramp accident study specifically on trucks has not been performed. However, the indication in the BMCS data is that trucks are overinvolved in loss-of-control accidents on ramps, suggesting controllability is main problem trucks experience on ramps.[18] However, the potential for collision accidents involving trucks on ramps may be no worse, or even better, than that of other vehicles. A summary of reports on accidents experienced by tractor, semitrailers on expressway ramps is presented in references 16, 18, 19, 20, and 21.

b. Truck controllability related to geometric design: An FHWA project examined truck controllability problems on ramps and to relate them to geometric design.[16,19] The individual accident reports from each ramp were examined closely to locate the approximate point on the ramp loss-of-control events occurred. Specific curves or transition areas on each ramp were given attention. A comprehensive simulation of the dynamic behavior of heavy-duty trucks was carried out. Inputs were the geometric data needed to completely define the curvature, superelevation, and grade of each ramp section of interest.

The tractor-semitrailers were simulated at various speeds and the gross motion response of the vehicle was then interpreted in terms of a likely loss-of-control outcome. One can conclude a substantial number of truck drivers tend to take ramps too fast for many reasons.[19]

These ramps accidents depend largely on the interaction between highway geometrics and vehicle dynamic behavior. The results of combined study of accident data, simulated vehicle response, and geometric details of ramp design indicate maneuvering limits of certain trucks are quite low relative to automobiles; therefore, current practice in ramp design leaves an extremely small margin for control of heavy vehicles.

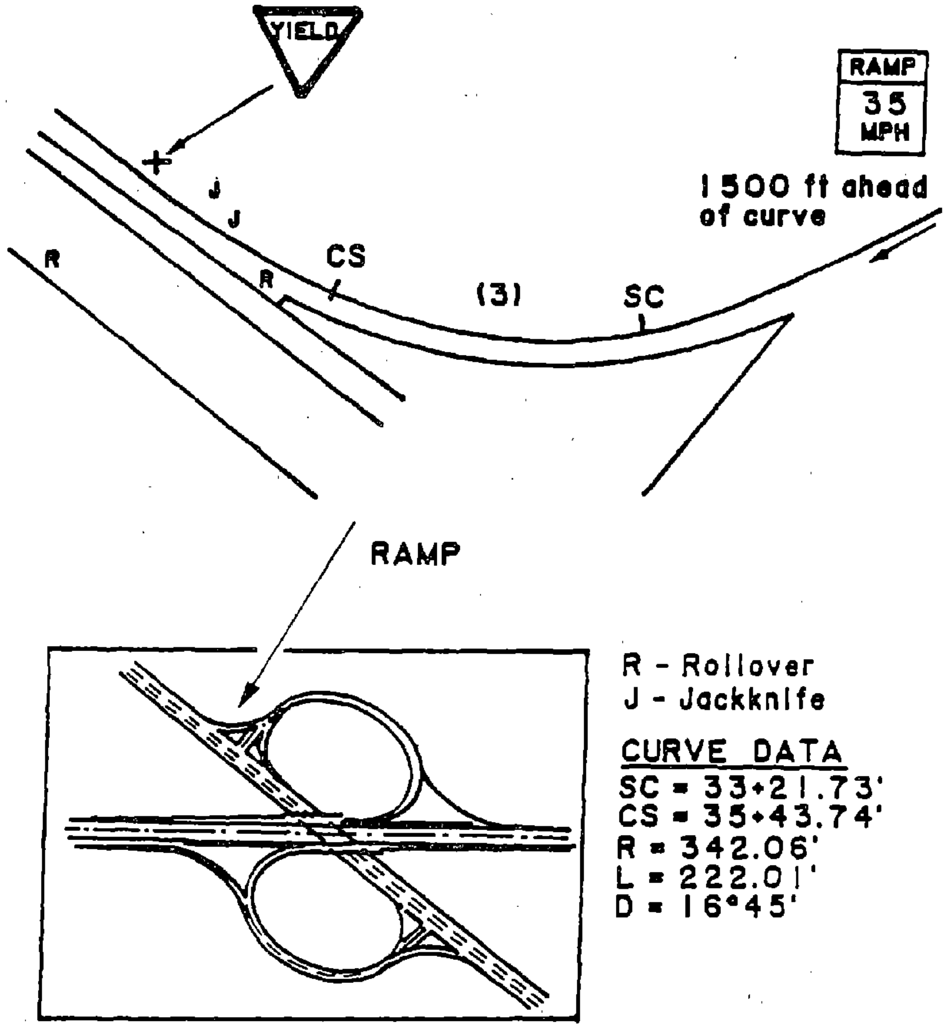
In addition, the FHWA research study recommended all AASHTO policies relating to the geometric design of highway ramps and other curved roadways be examined from the viewpoint of maneuvering requirements of other trucks.(16) State highway agencies are encouraged to survey interchange ramps within their jurisdictions in light of the study's findings, especially where sites have experienced frequent loss-of-control truck accidents.

Any ramps with trucks carrying hazmat, particularly in areas where a release would have serious consequences, should be surveyed with high-risk or catastrophic potential in mind. Further, these areas should be considered for barrier rail of the type that will contain 80,000-lb (31,936 kg) tank trucks.

Five specific cases should be examined. These cases are presented in detail, with each case being characterized by the particular aspect of ramp design that appears to be connected with truck control problem of interest.(16)

- Case 1 pertains to excessive side friction factors, given the roll stability limits of many trucks (figure 17).
- Case 2 deals with truckers' assumptions that ramp advisory speed does not apply to all curves on the ramp (figure 18).
- Case 3 involves the deficiency in deceleration lane lengths resulting in excessive speeds at the entrances of sharply curved ramps (figure 19). The consequence is roll-over or jackknife accidents.
- Case 4 deals with the sensitivity for hydroplaning on high-speed ramps (figure 20). Heavy duty vehicles are known to be unusual in their potential for loss of control on wet pavements.
- Case 5 deals with an obstacle that may trip and overturn articulated truck combinations due to curbs placed on the outer side of curved ramps (figures 21 and 22).

These cases fall either into the category of inherent limitations in truck stability and control or of truck driver behavior, which appears to frequently involve peculiar misjudgments. They are summarized below from the



1 ft =0.305 m
1 mi/h = 1.61 km/h

Figure 17. Layout of a site that poses a challenge to the truck-roll stability level.[16]

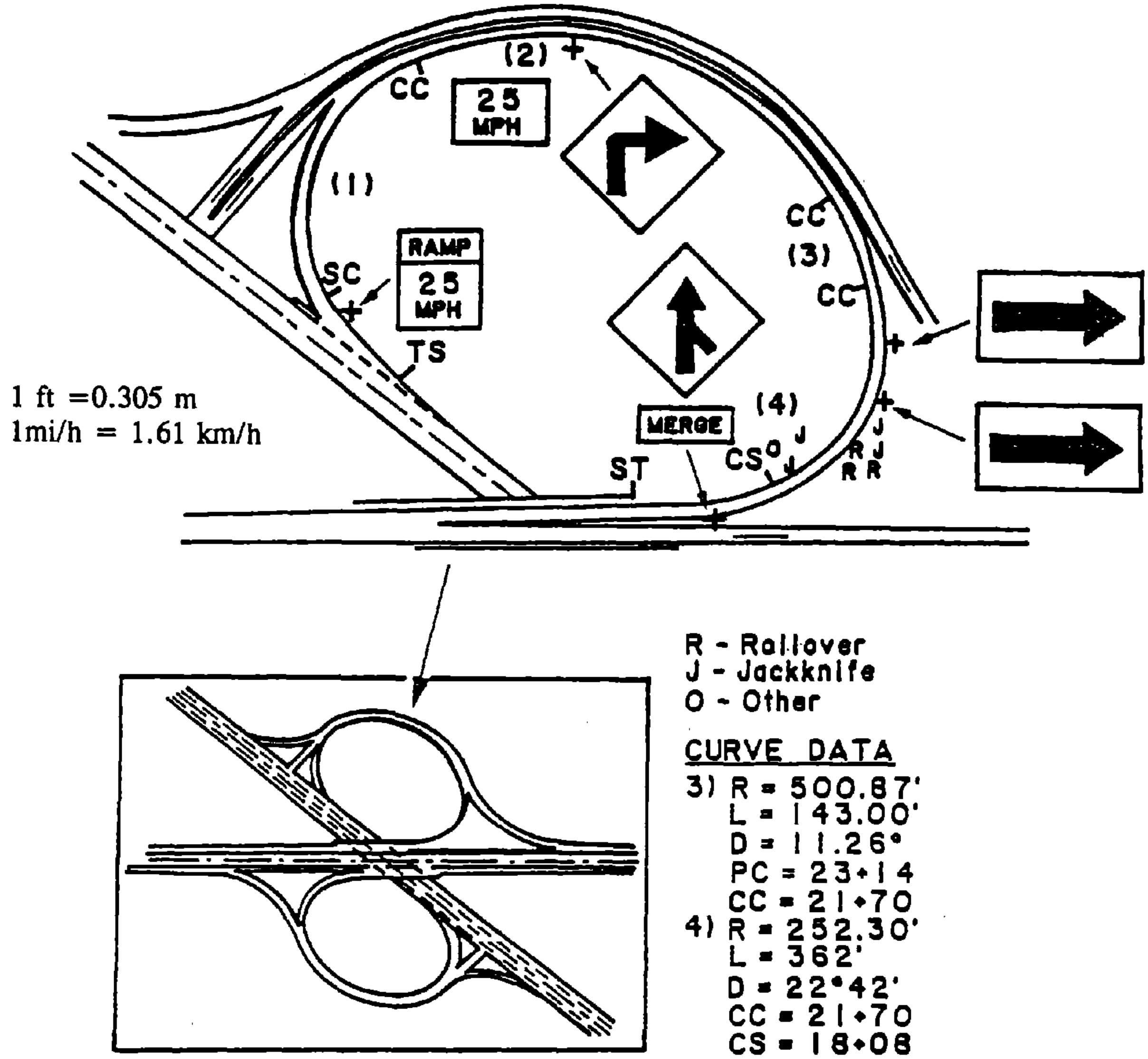


Figure 18. Layout of compound curve ramp.[16]

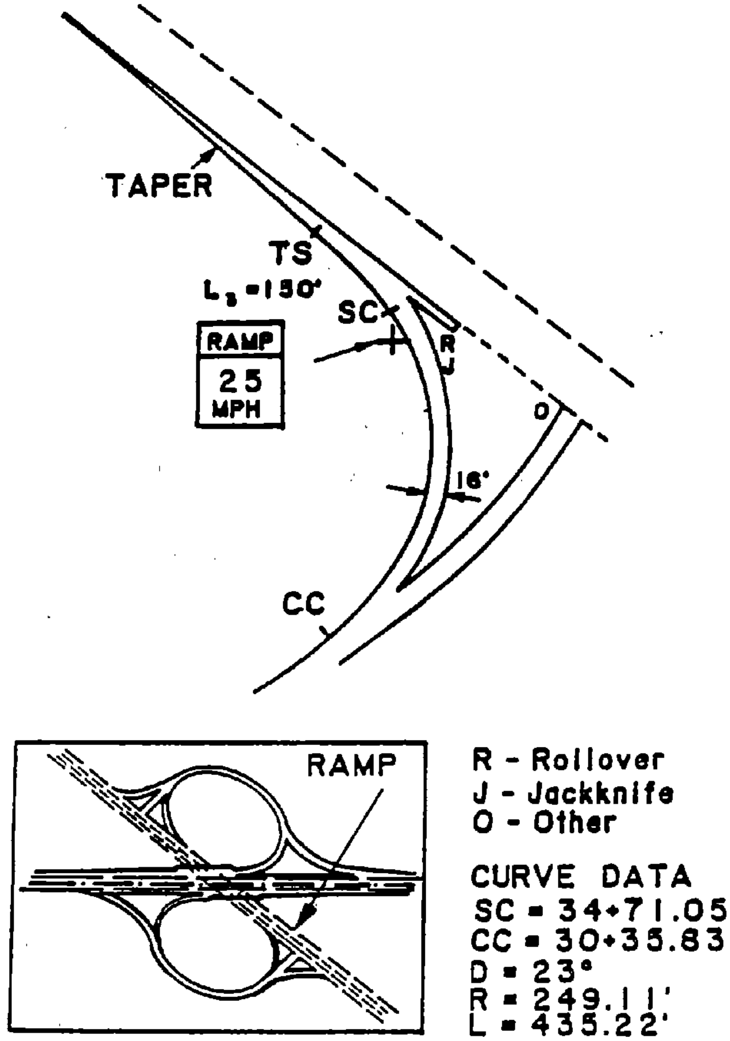


Figure 19. Layout of ramp with tapered deceleration lane.[16]

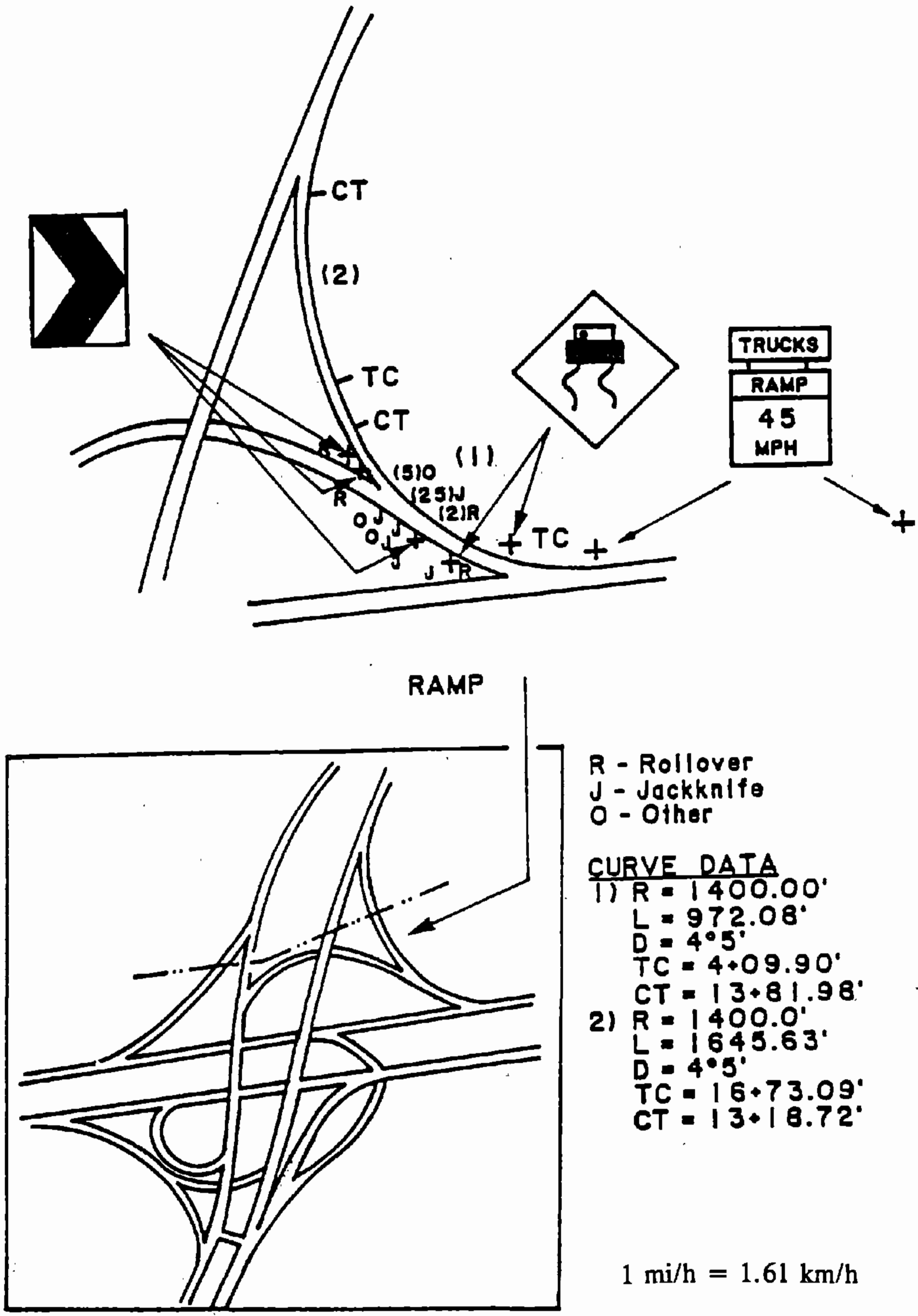


Figure 20. Layout of curved ramp site at which numerous loss-of-control accidents occurred with tractor-semitrailers during wet weather.[16]

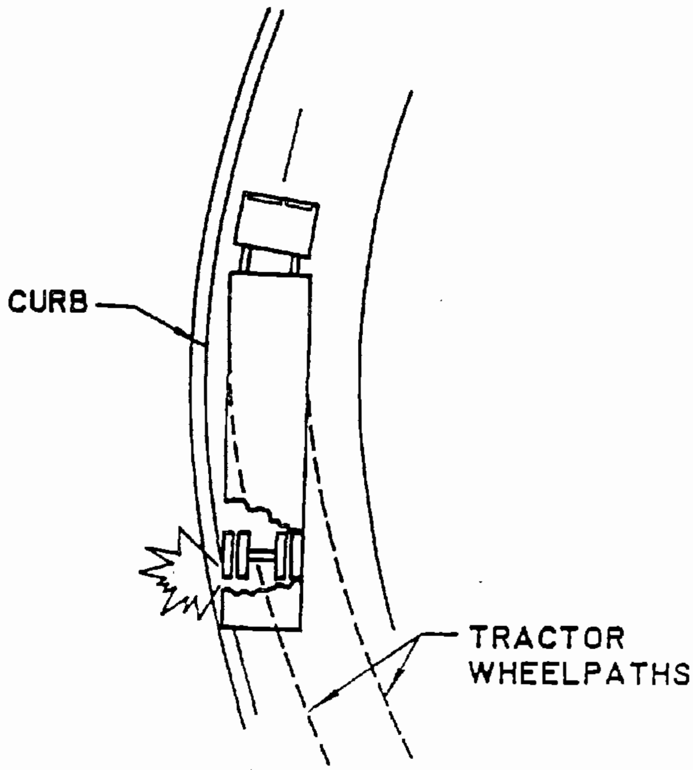
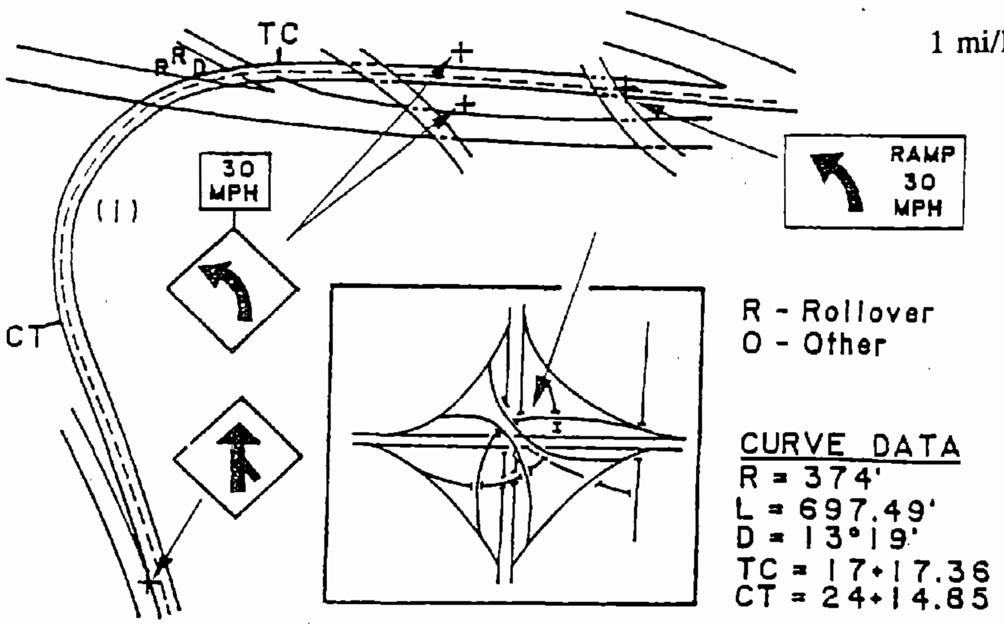


Figure 21. Outboard off tracking of semitrailer that leads to contact between trailer tires and an outside curb.[46]



1 mi/h = 1.61 km/h

Figure 22. Layout of a typical ramp on which curb-contact accidents often occurred.[17]

above referenced report. Where trucks carrying hazmat are present, and the consequences of an incident would be severe, high-strength barrier rail at critical points should be considered.

a. Case 1 (Side friction factor is excessive given the roll stability limits of many trucks.)

Figure 17 shows the exit ramp in which curve 3 is preceded and followed by spiral transitions with a posted advisory speed of 35 mi/h (56.4 k/h). The R and J positions indicate the approximate points at which vehicles involved in roll-over and jackknife accidents came to rest. According to the simulation results, the tractor-semitrailer at 35 mi/h (56.4 k/h) experiences a near roll-over, and the vehicle barely makes the turn. Because the superelevation is not fully developed along the spiral transition, the peak side friction factor of 0.21 at the point of curvature (SC) corresponds to a demand level of 0.24, allowing for steering fluctuations. At the final superelevation value of 0.08 ft (24 m), the curve would be characterized by a nominal friction factor of 0.16, which agrees with the AASHTO recommendation of a maximum of 0.155 for the side friction value in curves posted at 35 mi/h (56.4 k/h) Considering loaded, heavy vehicles exhibit static rollover threshold levels as low as 0.24, the suitability of a design policy that allows friction factor levels of 0.155 (or 0.16) is questionable. It is clear the maximum recommended values of the side friction factor have been set by AASHTO primarily to avoid driver discomfort. Apparently, this policy intends a substantially larger margin than is achieved with heavy trucks at the lower end of the stability spectrum. The low stability of trucks derives, of course, from the height (H) of the center of gravity of the combined payload and tare vehicle relative to track width (T) and a host of other sensitivities involving the compliance of tires, suspensions, fifth wheels, and frames.

b. Case 2 (Truckers assume ramp advisory speed does not apply to all curves on the ramp.)

Many ramps involve multiple curved segments with differing side friction factor demands, although only one ramp speed is generally posted. Consequently, truckers may presume at some point along the ramp they have passed the curve or curves that warranted the low posted speed. Subsequently, they begin to speed up in preparation for the merging task, only to find the remaining curve(s) at least as demarding of the low advisory speed condition as was the preceding portion of the ramp.

An example of such a case is the ramp shown in figure 18, comprised of a loop with four curves within a partial cloverleaf, rural interchange. The ramp is posted at 25 mi/h (40.3 k/h), with two sharp curves at either end and two intermediate curves with more moderate radii. The essential data for each of the four curves is listed in table 15.

Table 15. Data for four curves of figure 10.[16]

Curve No.	Radius--ft (m)[1]	Length--ft (m)[1]	Side Friction Factor
1	250 (76.2)	435 (132.6)	0.09
2	520 (158.2)	993 (302.7)	0.003
3	500 (152.4)	143 (43.9)	0.003
4	252 (76.8)	362 (110.4)	0.09

[1]Values have been rounded off in this table.

Truck accidents that occur on this ramp are all clustered at the approximate mid-length location of curve 4. Because the side friction factors for curves 1 and 4 are identical, truck drivers, after reasonably satisfying the speed requirements of curve 1, apparently misjudge the continuing need for low advisory speed while traveling the 1,100 ft (335.4 m) through the mild curves (curves 2 and 3). According to the analysis, a high-CG tractor-semitrailer would roll over in curve 4 if the driver permitted his speed to exceed 34 mi/h (54.8 km/h).

The number of jackknife accidents reported at this site equal the number of roll-over incidents, suggesting heavy braking is probably applied when the driver perceives that general loss of control is imminent. During such a misjudgment, the truck is particularly vulnerable because of the small tolerance the low-stability vehicle has for increased side friction factors.

c. Case 3 (Deceleration lane lengths are deficient for trucks, resulting in excessive speeds at the entrance of sharply curved ramps.)

The study of truck accidents on ramps has indicated cases of inadequate deceleration lengths available for trucks, and the cases that aggravate the problem are those in which the ramp incorporates a rather sharp curve right at the end of the deceleration lane, so a low advisory ramp speed must be achieved very quickly after departure from the through roadway. Figure 19 shows an example of such an exit ramp with a 249-ft (75.9 m) radius, a maximum superelevation value of 0.08 ft (.0024 m) and a side friction factor of 0.13. The tapered exit begins 375 ft (114.3 m) ahead of the point of curvature and allows no distance for delay in brake application beyond the leading edge of the taper. It assumes the vehicle will begin decelerating while still placed fully in the through lane.

Truckers who fail to achieve the required speed entering this curve will most likely roll over. The accident data, however, reveals both roll-over and jackknife accidents occur at the beginning of the example curve. The jackknife accidents simply result from the over-braking behavior of truck drivers to achieve a speed low enough to avoid roll-over. Simulation results show a tractor-semitrailer carrying freight at a more or less typical level of CG passes through the curve easily at 25 mi/h (40.3 km/h) but barely escapes roll-over at 35 mi/h (56.4 km/h). A great deal of evidence establishes the braking capability of heavy-truck combinations is quite low. Also, under partial loading conditions, a vehicle can exhibit both a low level of roll stability and an extremely poor level of braking capability.

The AASHTO policy for length of deceleration lanes clearly provides for more relaxed braking conditions than those required by the ramp in this example. However, the truck drivers could make a compromise by simply applying brakes throughout the available length of lane and foresaking a 3-second period of coasting in gear.

d. <u>Case 4</u> (Lightly loaded truck tires are sensitive to pavement texture causing hydroplaning on high-speed ramps.)

For light tire loads associated with empty truck combinations, the footprint with which a truck tire contacts the pavement is usually incapable of expelling water. Since the loss of tire traction on wet surfaces is clearly most pronounced when speed is high, potentially troublesome ramps are categorically those with large-radius curves such as interchanges between two high-speed highways. The applicable scenario leading to loss of control involves an unloaded truck; a high-speed turn posing a substantial side friction demand; and poor pavement texture or water drainage characteristics or both.

Figure 20 illustrates the above phenomenon. The ramp consists of a curve of 2,600 ft (792.7 m) in length, comprised of two curve segments of 1,400-ft (426.8 m) radii with a 290-ft (88.4 m) tangent section connecting the two.

Although the advisory speed is 45 mi/h (72.5 k/h) evidence suggests many trucks simply sustain the 55 mi/h (88.6 k/h) speed posted for other vehicles. Forty-four loss-of-control accidents occurred at this site with tractor-semitrailers during a 2-year period following of a new roadway, and all these accidents occurred when the pavement was wet. Of those accidents, 32 involved trucks jackknifing, 5 culminated in roll-over, and 7 involved other events such as simply running off the road or striking a guard rail. The ramp was resurfaced at the end of this 2-year period with a high-friction bituminous concrete overlay, and the wet-weather accident problem essentially disappeared.

e. Case 5 (Curbs placed on the outer side of curved ramps present obstacles that may trip and overturn articulated truck combinations.)

Trailers in tractor-semitrailer and doubles combinations tend to "fling out" in a turn as the lateral acceleration level increases. The rear-most axles may actually subtend paths outboard of those traced by tractor axles. One of the major concerns is that rear-most axles may strike a curb situated on some ramps along the outer side of the curve. The safety problem may be aggravated by the natural instinct of drivers to steer close to the outer curb, believing the trailer axles always tend to go inward.

Figure 21 shows the outer trailer tire approaching the curb at a side slip angle, with the tire pointed away from the curb rather than toward it. Figure 22 illustrates a case in which truck roll-over accidents appeared to involve tripping at an outside curb. The ramp involves two 12-ft (3.7 m) lanes constituting an interchange leg between two urban expressways. The curve radius of 374 ft (114.02 m), together with a super elevation of 0.05 and an original ramp advisory speed of 35 mi/h (56.4 k/h), yielded a side friction factor of 0.17.

D. Entrance and Exit Ramps Design Considerations

1. General considerations

In situations where median openings are not provided over long distances, the hazardous material accident response team may have to find its way to the accident site by making use of an entrance or exit ramp. Use of an entrance/exit ramp by the response team may also be necessary when an accident involving hazardous material leads to a traffic jam. Upon entering a highway using an exit/entrance ramp, the response team can move either with or against traffic.

Cases a(1) and b(1) shown in Figure 23 would be possible without any design modification. However, special design considerations may be necessary to make cases a(2) and b(2) feasible. Design for these cases would mainly involve widening of curves along with proper radius of curvature as shown in figures 23 and 24. Negative super elevation at these points for a "wrong-way" movement could be another point of concern, but at a low turning speed of about 1 mi/h (1.61 k/h) around these curves, the super elevation problem could be assumed to be insignificant. Emergency response vehicle drivers should be aware of this condition, using caution and limiting their speed.

2. Geometric design for curve widening/radius of curvature for minimum turning paths of design vehicles

The principal dimensions affecting design are the minimum turning radius, the tread width, the wheel base, and the path of the inner rear tire. Effects of driver characteristics, such as the rate at which the driver approached centripetal acceleration and the slip angles of wheels, are minimized by assuming the speed of the vehicle for the minimum radius (sharpest) turn is less than 10 mi/h (16.1 k/h).

The boundaries of the turning paths of a design vehicle when making the sharpest turns are established by the outer trace of the front overhang and the path of the inner rear wheel. This assumes the outer front wheel follows the circular arc defining the minimum turning radius as determined by the vehicle steering mechanism. The dimensions in this report are for single unit trucks (SU). The minimum radii of the outside and inside wheel paths are given in table 25. Figure 25 sketches the minimum turning dimensions for a single unit truck, and figure 26 shows the minimum width of pavement required at turning for such a vehicle. Checking the type of emergency response vehicle in an area should verify the SU design vehicle template is adequate. If not, it will have to be modified because an emergency vehicle with a unique turning path may require other specific dimensions.

The proposed geometric modifications for emergency entry of a hazmat response truck through an exit ramp and movirg in the direction of flow is

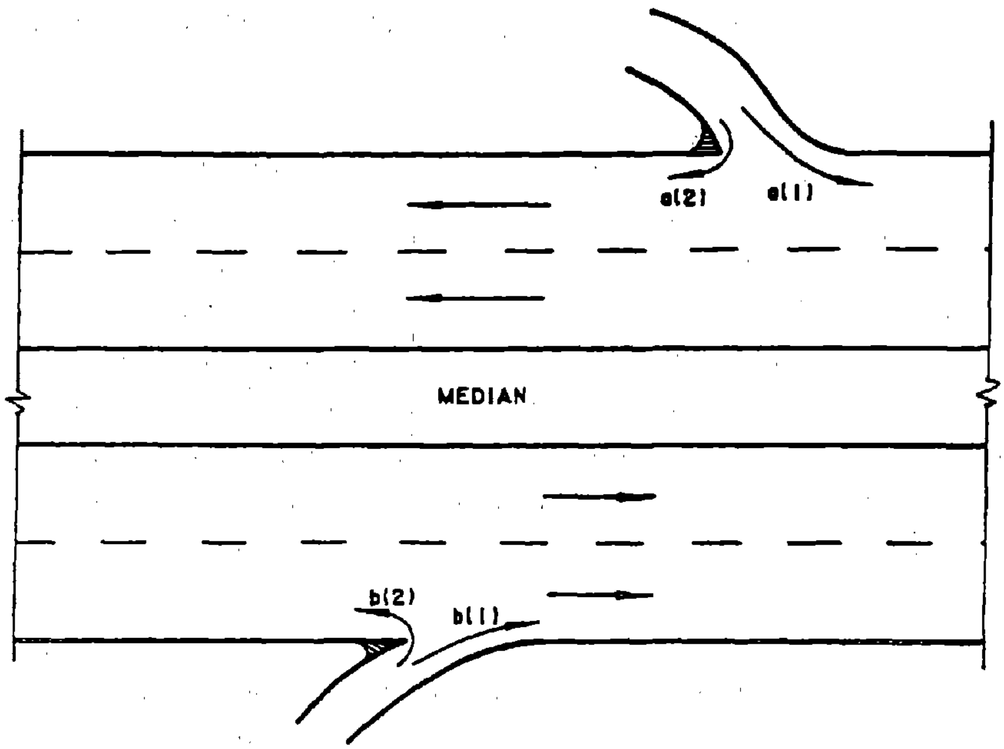
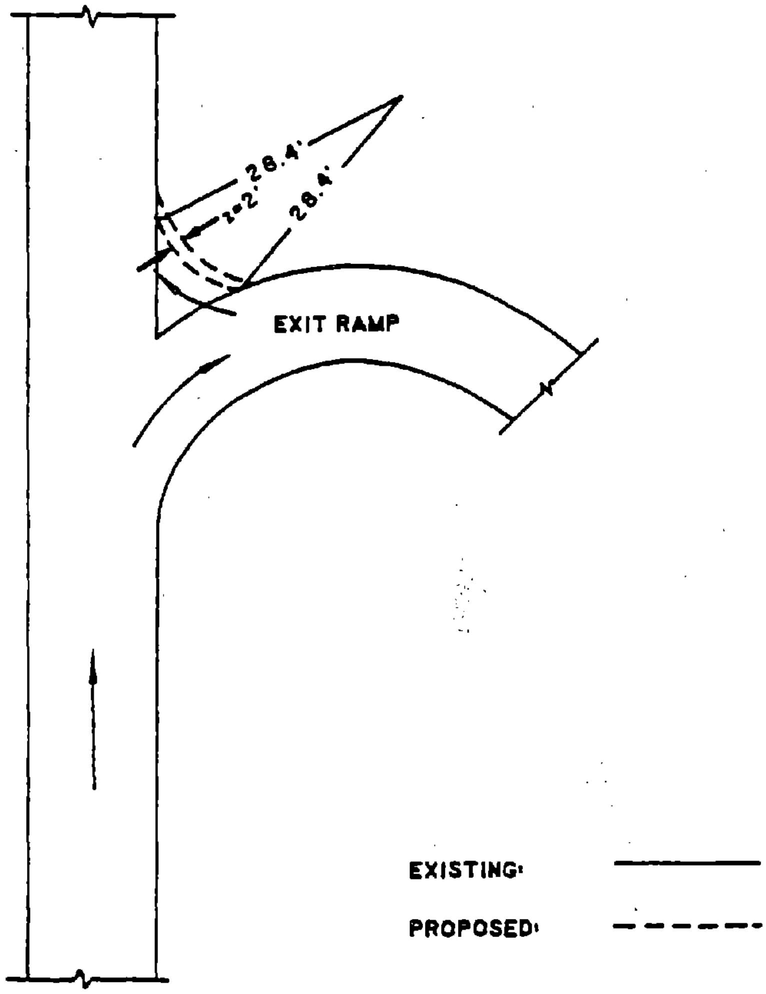
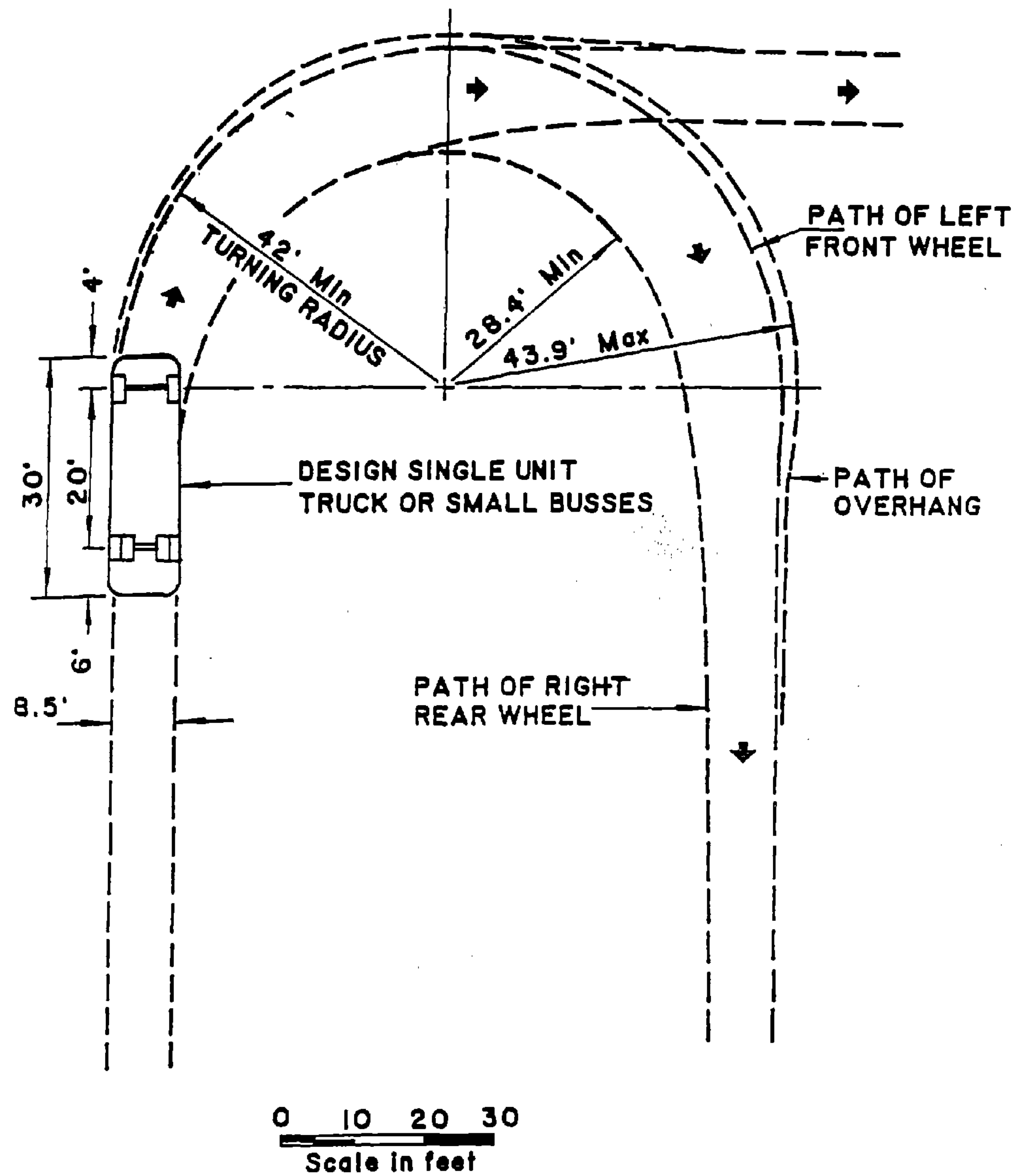


Figure 23. A sketch of the possible, desirable directions of travel for emergency vehicles.



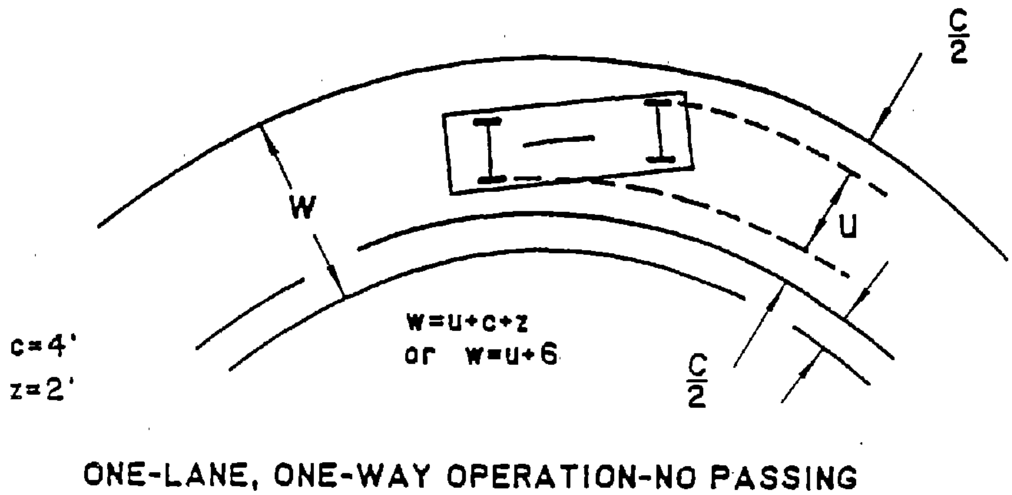
NOTE: THE DIMENSIONS SHOWN ARE THE MINIMUM REQUIREMENTS.

Figure 24. Details of turning radii for emergency vehicles based on a single unit design vehicle.



1 ft = 0.305 m

Figure 25. Minimum turning path for a single unit design vehicle.[17]



1 ft = 0.305 m

Figure 26. Details of curve width required for a single unit design vehicle.[17]

Table 16. Minimum turning radii of design vehicles.[17]

Design Vehicle Type	Passenger Car	Single Unit Truck	Single Unit Bus	Atricu-lated Bus	Semi trailer Inter-mediate
Symbol	P	SU	BUS	A-BUS	WB-40
Minimum turning radius ft (m)	24 (7.32)	42 (12.8)	42 (12.8)	38 (11.6)	40 (12.2)
Minimum inside radius ft (m)	15.3 (4.7)	28.4 (8.7)	23.2 (7.1)	21.0 (6.4)	19.9(6.1)

Design Vehicle Type	Semi-trailer Combina-tion Large	Semi-trailer Full-trailer Combina-tion	Motor Home	Passen-ger Car with Travel Trailer	Passen-ger Car with Boat and Trailer
Symbol	WB-50	WB-60	MH	P/T	P/B
Minimum turning radius ft (m)	45 (13.7)	45 (13.7)	42 (12.8)	24 (7.3)	24 (7.3)
Minimum inside radius ft (m)	19.8 (6.0)	19.8 (6.0)	28.4 (8.7)	5.5 (1.7)	10 (3.1)

shown in figure 24. These dimensions are in accordance with standard design practice. However, the extra width allowance due to the difficulty of driving on curves is not mandatory in this case, as the vehicle will have enough space for its maneuver on the left side. In the figure, the existing systems are shown by continuous lines and the dotted lines represent proposed reconstruction.

E. Alinement, Construction, and Maintenance of Highway in Water Catchment Areas

1. Background

This section is based on a German report on protecting potable water supplies.[22] It is important because it specifically addresses mitigation of hazmat runoff into potable water supply areas and sensitive environmental areas. Germany has much stricter policies and laws protecting water supplies. These points give the reader some insight into what would be required to implement a policy of full containment; i.e., a design to keep hazmat carrying vehicles within the highway right-of-way in case of an accident and a closed highway drainage system to fully contain water-contaminating material spilled in a release. (Unless specifically noted otherwise, all material in section E is from the above referenced German report.)

German law requires that highway alinement must avoid designated sensitive water catchment areas (any part of the watershed feeding a potable water supply) if possible. If not possible, the highway must be designed to ensure hazmat carrying vehicles having an accident will be contained within the right-of-way by barrier rail, berms, etc. In the case of a spill occurring (incident), the spilled material will enter some closed drainage system that must be provided to prevent any spilled material from entering the water supply by surface runoff or groundwater transport.

A closed system is something more State highways will have to consider. It is often needed to protect water supplies or sensitive environmental areas.

The German report is quite lengthy and not available in English.[22] Thus, presenting its main points herein should be of value. However, any State with these problems should probably obtain and translate the report. Only select sections of the German report were translated. Although every attempt was made not to, some points were possibly misinterpreted or taken out of context. The danger to water supplies or sensitive environmental areas resulting from water contamination due to traffic can be divided into two groups:

- The main result is the accumulative contamination of the highway surface by exhaust fumes and oil leakage from vehicle engines, as well as particle from the abrasion of the road surface and tires.
- Unpredictable contamination based on type, location, and proportion of incidents where water-hazardous material is released.

The latter group is of primary concern in the German report. Thus, systems discussed in the German report are applicable to this guide.[2]

The German report breaks protective measures into two groups: 1) active measures that directly stop the contamination of the highway surface as much as possible, and 2) passive measures that slow or eliminate the consequences of contamination.

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[2]The only study of this nature in the United States involved a closed system by the Rhode Island Department of Transportation (RIDOT) to determine the feasibility of building a 2-mi section of U.S. Route 6 across the Situate Reservoir. After determining the risk and comparing the risk to system's cost, it was not built because the cost was considered excessive.[23,24]

Active measures include those that reduce the normal vehicle contamination as well as minimize contamination from spills. "Active" and "passive" may not be the best English words from the translation, but they relate well to the terms "preventative" and "mitigating," respectively, used earlier in this report to break down protective systems that prevent contaminating materials (including hazmat) on the road surface, or mitigate the consequences once they are on the road surface. The German report emphasizes good alinement to control these, using all the principles that apply to a smooth, safe ride.

Protective systems should be used in areas where a spill could cause long-term damage to a potable water supply or sensitive environmental area. Contaminations caused by transport accidents can be avoided by measures that prevent or mitigate the consequences of accidents.

In addition to good design and construction practices in general, measures must be taken for highways on dams and/or elevated areas. The side slopes should be as shallow as possible. Barrier-rail should be incorporated along the median and along the shoulders.

In highways in low lying areas, the permissible thickness of natural soil left above groundwater depends upon the geological formulation and on hydrological conditions of the subsoil. The roadbed has to have a sufficiently thick upper layer of soil cover above the groundwater. There are no appropriate general thickness values known to the authors. Studies of specific materials and soil types should be made. When judgment concludes a sufficient upper layer or soil cover does not exist, the subsoil has to be sealed up to a required thickness by constructing a watertight protection layer made of impervious material.[3] The German report recommends 25.5 in (60 cm).

Rainwater draining off slopes should be collected in impervious ditches and channeled away into the controlled highway runoff. The soil in the ditches and the soil areas between these and the roadway area should be sealed with an impervious soil blanket at least 25.5 in (60 cm) thick. On bridges, pipes should be used to collect and channel runoff to properly designated receptors.

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[3]The thickness needed would depend on the rate of perculation of the soil and how many days were considered safe before the infiltrating liquid reached the groundwater--a function of anticipated response time to correct the situation. More research is needed in this area.

This section shall now concentrate on physically containing or mitigating the consequences of hazmat spills. The chemical interactions of water and hazardous materials and mitigation by chemical reactions are beyond the scope of this report. People with expertise in these countermeasures can usually be found in State emergency response organization or Environmental Protection Agency (EPA) offices.

One general mitigation consideration is in the area of communications. To facilitate quick reporting of an accident by the motorists present, the German report recommends that emergency phones should be installed not more than 3,280 ft (1,000 m) apart on Interstates in their designated water protection areas. A quick response often prevents greater damage. A policy with important routes through water protection areas should be given special consideration such as emergency phones and response stations (manned or unmanned) constructed and equipped with simple tools (shovels, buckets,plastic bags) and with oil-binding material (sawdust, haybales) quickly available in emergencies.

In the United States, emergency response decisions are not usually made by departments of transportation. The key emergency response organization may differ in each State. It would be advisable, however, for the State highway administrators to make contact with the appropriate State emergency response agency in regard to these matters.

2. Mitigation by containment procedure

Hazmat may be in the form of a solid, liquid, or highly volatile material or gas. A solid on the ground involves only scooping up the substance and transporting it to a disposable area. However, this must be done by experienced response personnel and in accordance with all existing regulations. Again, the appropriate State, emergency response agency should be consulted.

To contain hazardous vapors in the atmosphere is almost impossible, and stopping the leak as quickly as possible is the only logical approach. Motorists and other persons at risk should be evacuated. Again, officials in charge of coordinating State response should be consulted.

Many hazmats are heavier than water or soluble. For soluble materials, the only practical approach would be containment by holding tanks of reservoirs of adequate capacity that can be isolated from regular storm drains should a spill occur.

Sedimentation basins installed at the junction of secondary drainage network systems can effectively take care of removing substances that are heavier than water. Such a system in the United States is shown in figure 27.[25]

Petroleum oils are the most likely hazmat to be spilled. Most petroleum oils float on water and are highly insoluble. There are several different configurations of oil separators. An example including an oil separator in the drainage system is shown in figure 28. A basic decision in sizing the basin is to decide on the amount of rainfall runoff that should be contained along with the hazmat, in the case of a hazmat spill during a rainstorm.

The sections of an oil separator are shown in figure 29. The volume that maintains a given increase in velocity is determined. In the case of a basin designed for retaining rain, only the volume needed for storage is the water quantity resulting from maximum difference between inflow and outflow.

One of the functions of a basin that retains rainwater runoff is to safeguard the main drainage by using a design capacity that includes rainwater drainage peaks. A study done for Rhode Island recommends the basins be designed for back-to-back 100-year rainfall quantities.[24]

The construction of a rain overflow in an urban area is related to case 1a in figure 28. Two possibilities to retain a design rainfall are present in the case to retain oil: 1) construction of a submerged wall, or 2) a series connection of basin or oil separator. The latter case has the advantage that the oil separator is subject to a fixed maximum reduction in quantity of flow and thus could be designed smaller.

Also, it would be advantageous to have a good estimate of the quantity of leakage during an accident of a vehicle, considering the type of damage to the vehicle and its capacity. No reliable data is available on spill quantities on U.S. highways. The German study showed the following results:

In a 6-year period, the spilled materials per accident are as follows:

$$\text{Tanker} = \frac{3573.85}{1239} = 2.890\ \text{m}^3/\text{accident}\ (762.81\ \text{gal};\ 101.98\ \text{ft}^3) \qquad (14)$$

$$\text{Trucks with an attached tank} = \frac{443.49}{309} = 1.45\ \text{m}^3/\text{accident}\ 37.88\ \text{gal};\ 5.06\ \text{ft}^3) \qquad (15)$$

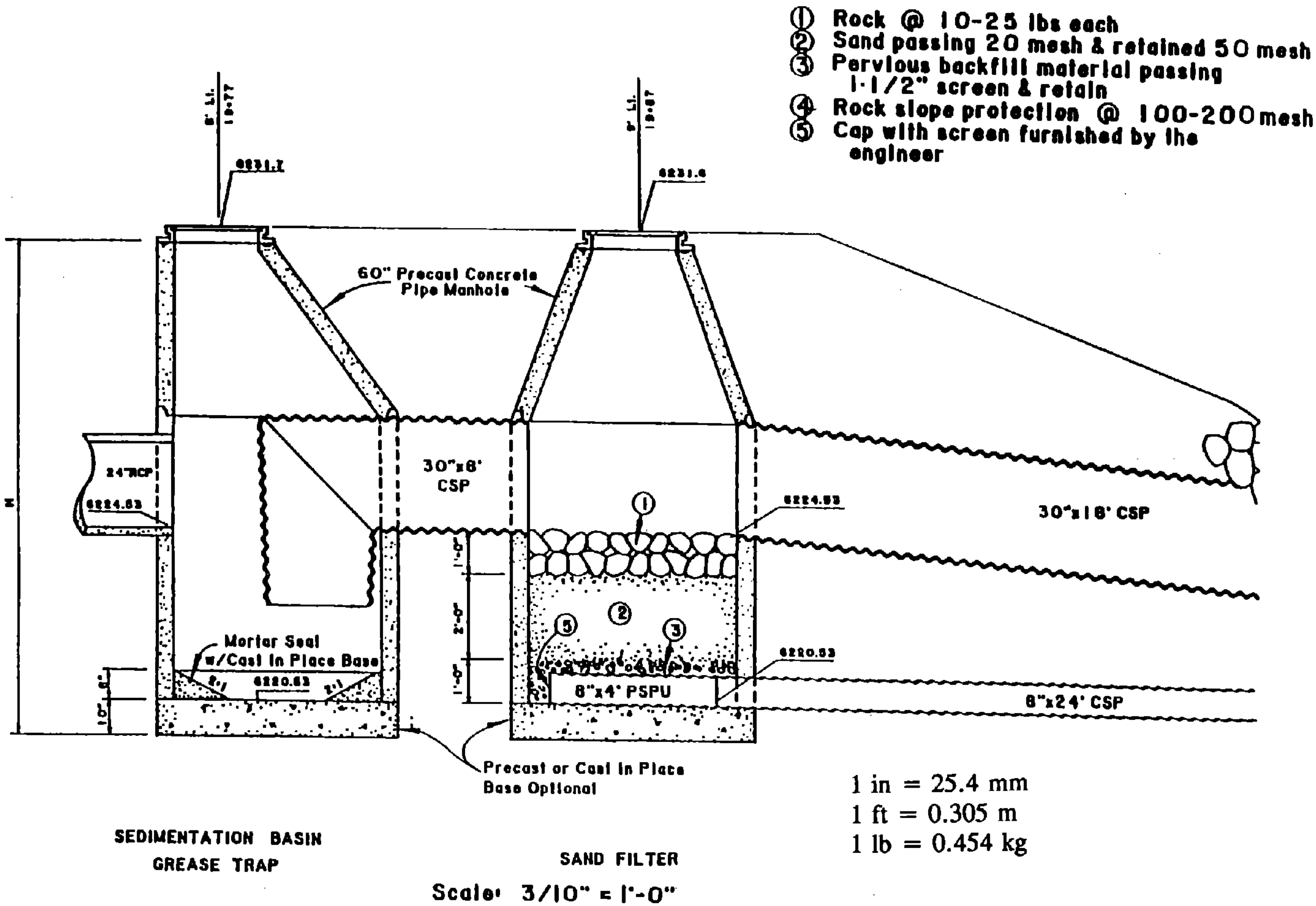
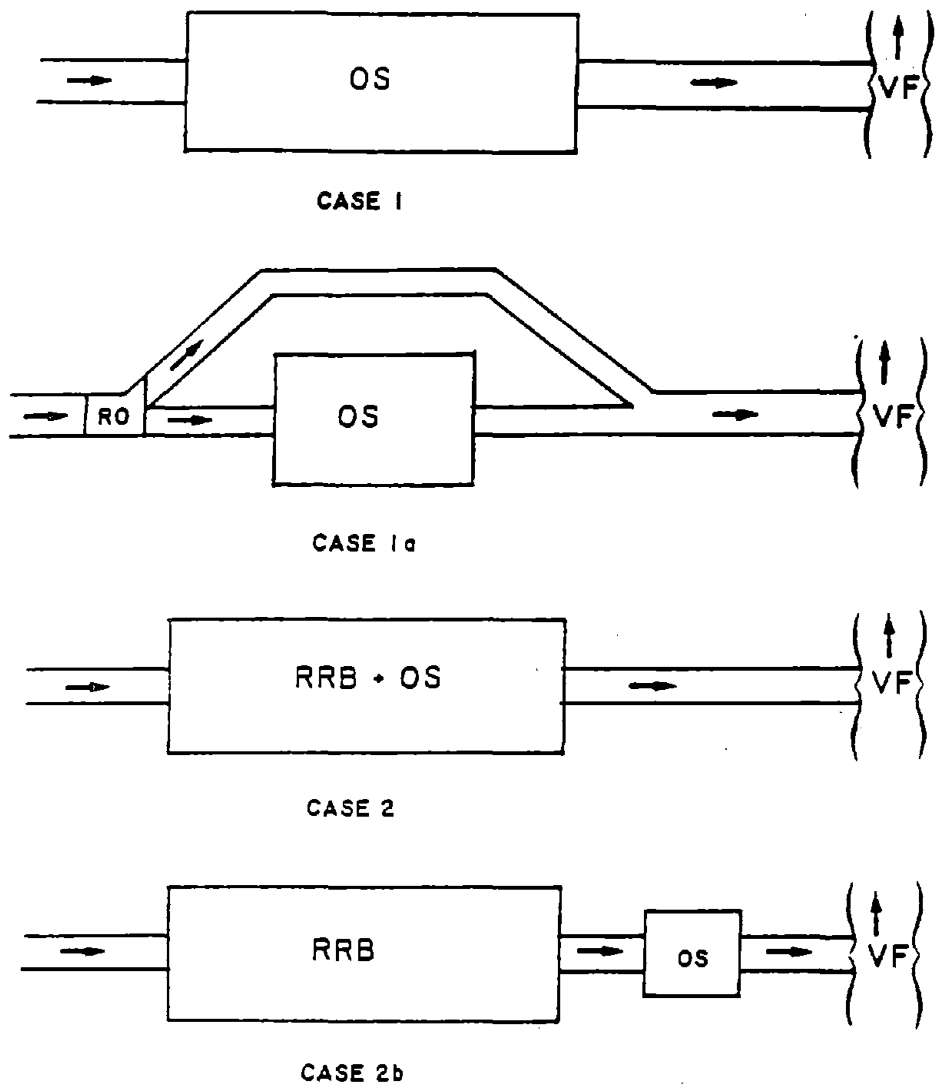


Figure 27. Sedimentation basin with grease trap and sand filter.[25]



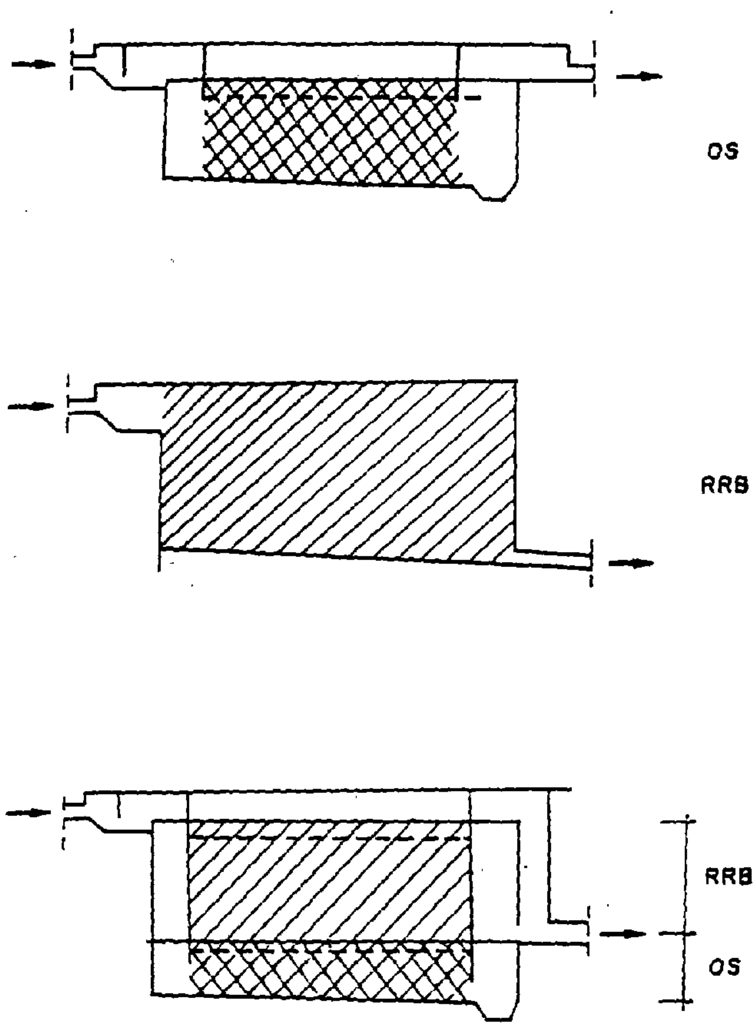
OS = OIL SEPARATOR

RRB = RAIN RETENTION BASIN

RO = RAIN OVERFLOW

VF = MAIN DRAINAGE

Figure 28. Special types of oil separators.[22]



Functions of the basin

OS = Oil separator

RRB = Rain retention basin

Figure 29. Sections of an oil separator. [22]

Other street vehicles $= \frac{353.65}{870} = 4.05\ m^3$/accident (106.90 gal; 14.29 ft^3). (16)

The average value of all vehicle accidents reported is

$$\frac{4369.99}{2418} = 1.810\ m^3\text{/accident (477.75 gal; 63.87 ft}^3\text{)}. \quad (17)$$

Less than one-half of the contents of a single tank compartment leaks out in the average incident--500 gal (1.89 m^3). Research is needed to get a reliable figure for U.S. tank trucks.

If oil gets into the drainage channels it results in an "oil in water mixture" depending on the radius of the dispersed particles, there is a differentiation between precipitated parts, emulsified parts, and soluble parts. Usually, over 90 percent of a "rainwater-oil-mixture" reaches an oil separator after an accident. The percentage of soluble and emulsified substances is comparably low.

When dealing with water soluble hazardous materials, oil separators and sedimentation basins, etc., are not effective. In such cases, the material must be prevented from entering the water reservoir by providing drains that lead to a separate holding basin.

3. Discussion on probability[22]

Before any discussion on containment systems is complete, oil-separator capacity has to be determined based on the following known or assumed parameters: 1) the vehicle size, 2) a designated water protection area, 3) the vehicle passes during a rainstorm, 4) a specified quantity of rain, 5) the vehicle has an accident, and 6) oil leaks out (incident).

These relations are stated as a function as follows:

oil separator = vehicle ^ drives ^ protection area ^ rain ^ quantity of rain ^ accident ^ oil leakage.

(^ = conjunction or "as well as")

One can decide the need to construct an oil separator only if one "expects" a positive answer to all received parameters. Even if there is one negative answer, construction may be rejected (a management decision).

The probability, P, for conditions 1-6 above may be written:

$$P = P_{(vehicle)} \cdot P_{(protection\ area)} \cdot P_{(rain)} \cdot P_{(rain\ quality)} \cdot P_{(accident)} \cdot P_{(oil\ leakage)} \qquad (18)$$

where:

$$P_{(vehicle)} = \frac{\text{average number of cars driving at any time}}{\text{total number of vehicles}}$$

$$P_{(protection\ area)} = \frac{\text{size of water protection areas}}{\text{total area considered}}$$

$$P_{(rain)} = \frac{\text{number of hours of rain per year}}{\text{hours per year}}$$

$$P_{(\text{"x" quality of rain (or "x" runoff)})} = \frac{\text{number of hours of rain per year with "x" or greater quality}}{\text{number of hours of rain per year}}$$

$$P_{(accident)} = \frac{\text{vehicle accident per year}}{\text{total number of vehicles}}$$

$$P_{(oil\ leakage)} = \frac{\text{accidents with leakage of oil and other water-hazardous substances}}{\text{vehicle accidents per year}}$$

4. An example of an environmental protective system on bridges over waterways: improvements to Red Mill Road, from Hamlin Road to Old Oxford Road, Durham County, North Carolina[26]

Where protective systems are used in the United States specifically to mitigate hazmat liquid spills, only one closed system was found in conjunction with a proposed bridge over a waterway. Few details were available in its report. It appears the designers knew the system was less than perfect but consider it to be better than nothing. The biggest weakness is the manual shut-off valve.

The project was considered a "pilot project" for the design and incorporation of pollution control measures on bridges over environmentally sensitive waters. The proposed bridge will be 30 ft (9.2 m) wide, with an estimated length of 300 ft (91.5 m), and of cored-slab, flat-deck concrete construction without weep holes, thus preventing bridge runoff from flowing directly into the river. Instead, runoff will be directed to two sluice-gate controlled soil basins. The sluice gates will be normally open and must be shut manually if a spill occurs. It is assumed somebody who knows about the system, how to operate it and shut off the valves will be at the scene. If not, the system offers no protection.

The North Carolina Department of Transportation (NCDOT) has also adopted this system for installation in truck parking lots in highway rest areas. Rest areas are more likely than river crossings to have a knowledgable attendant on site who understands the system and can shut the sluice gate. For this reason, the system may be more effective at rest areas. However, the success of such a system depends upon response time of an emergency responder or State personnel who understand the system.(27) If response time to shut the valve is within the spilled material outflow time (flow out of the soil basin), it will be effective; otherwise, it is useless.

5. United States study of runoff mitigation measues

The only report in English addressing these specific issues is a 1980 California Department of Transportation (Caltrans) report on a study performed as part of an HP&R project.(25)

The study surveyed the 50 State transportation agencies to determine what mitigation measures were being used to remove chemical pollutants from various sources such as hazardous spills, constituents in pavement runoff water, leachates from mineral bearing soils, sandblasting old paint from bridges, etc. Responses supplied varying amounts of information for site-specific, special cases. Little or no information was directly related to mitigation of hazmat spills. A summary of the findings broken down by pollutant treatment categories is included in appendix E of this guide. This FHWA report should be readily available and studied if a State needs to consider adopting one of the systems associated with these categories of pollutant treatment measures.

F. Prevention and Control of Highway Tunnel Fires(28)

1. Introduction

As far as fires are concerned, highway tunnels are generally safer than open roads. There have been only two major tunnel fires in the United States, one resulting in fatalities.[4] Likewise, apparently only two incidents of major tunnel fires have been reported in the rest of the world. Because of this, a statistical basis for predicting the frequency of hazardous material

[4]In this section "major" signifies that the fire was uncontrollable or spread throughout the entire tunnel or major portions of it.

accidents/ fires in highway tunnels is very difficult to develop. The simplest recourse is to predict the highway tunnel accident/fire frequency on the same statistical basis used for the open highway accident/fires of hazardous materials.

Highway tunnel fires can involve either the tunnel structure and systems or the vehicles that pass through it. However, the nonflammable nature of the materials involved suggests all highway tunnel fires will continue to originate in vehicles and their fuel, cargo, and furnishings. In congested urban tunnels, small automobile fires are routine incidents, occurring as frequently as weekly and are generally extinguished without much difficulty. On the contrary, prevention and control of major tunnel fires is quite complicated.

2. Causes

Several reasons could be suggested for the number of accidents per-vehicle-mile apparently being lower in tunnels than on the open road:

- Tunnels are usually straight or gently curved at most.
- Intersections and interchanges usually are not present in tunnels.
- Tunnels are generally supervised and well-lit.
- Traffic is often slow and congested, perhaps reducing the chances for high-speed relative motion between vehicles.
- Drivers are circumspect in tunnels.

Combinations of cargo and tunnel groups need to be subjected to quantitative risk assessments before the most cost-effective fire prevention and control strategy can be specified.

3. Sources of ignition

Highway tunnel fires invariably originate in the vehicles using the tunnel. Accidents, mechanical failure, and human error have all been sources of ignition in the past. One cannot rule out the possibility of a criminal or mischievous action and sabotage. Multi-vehicle collisions have caused ignition of flammables. The impact in a rear-end collision, generally due to traffic back-up, may not be sufficient to cause a major fire. However, head-on collisions have resulted in fires, causing extensive damage.

Mechanical fire appears to be a common cause of vehicular fires. Broken fuel lines and electrical faults ignite as often in tunnels as on open roads, as do brake and bearing failures. The uphill grades of some tunnels have caused vehicle breakdowns, and carbuerator malfunctions have resulted in fires in slow moving traffic on the uphill grades.

Human error or inattention has also contributed to both accidents and fires in tunnels. Passenger-compartment fires resulting from careless smoking or similar mishaps are a common occurrence. Rubber tires and vehicles are flammable and may sometimes catch on fire in a tunnel. Cargos and furnishings--upholstery, suitcases, personal effects, etc.--can also be flammable.

4. Sources of fuel

Vehicles are fueled and lubricated by flammable liquids and will be for the foreseeable future. These fuels, lubricants, and their residues will always be a source of combustibles in tunnels.

5. Hazardous materials involvement and consequences

A fire may start in tunnels where flammable or hazardous materials are allowed. The flames from a hazmat fire in a highway tunnel will spread along the tunnel ceiling and the smoke will move through the tunnel, spreading heat and toxic gases away from the fire location. Consequently, air temperatures increase. This may cause secondary burns and even threaten human life. The intensity of a highway tunnel fire involving a spilled hazardous material depends on the area of spilled liquid, the availability of combustion air, and the ability of smoke to escape from the tunnel. The duration of the fire depends on the volume of available fuel, depth of the spilled fuel, or the spill flow rate.

If the spill involves a liquefied flammable gas, the fire can create a significant explosion potential within a tunnel. An explosion involving those vapors can create blast overpressures, possibly causing structural damage to the tunnel. (However, a study of blast effects on tunnels in Great Britain concluded structural damage was unlikely.) If cargo is poisonous, toxic, or nuclear material, its mere presence can be life-threatening, or its involvement in a mishap could result in a total loss of life in a tunnel. Also, flammable liquids and certain hydrocarbon-based solids generally catch fire easily upon exposure to ignition sources.

The chance of a fire or explosion occurring in a vehicle carrying a hazardous material is remote, but the magnitude of such a fire within a highway tunnel can be great.

The tunnel support systems, including lighting, emergency phones, signs, alarms, wiring, commercial broadcast antennae, firefighting water supply, etc., may get destroyed or severely damaged.

6. Risk analysis

The fire and explosion risk of a hazardous material tank truck in a highway tunnel is a function of the frequency and magnitude with which an incident may occur. A risk analysis was performed with the help of a reference tunnel 33 ft (10.1 m) wide, 16 ft (4.9 m) high, and 1 mi (1.61 km) long with a horizontal tunnel bore. The fire and hazardous cargo spill frequencies for the reference tunnel are predicted as:

- One cargo spill per 2,390,000 tunnel crossings.
- One cargo fire per 8,064,000 tunnel crossings.

Assuming that hazardous material tank truck crossings occur at the rate of 100 crossings per day (36,500 crossings per year), the hazardous material fire and spill frequencies are predicted as:

- One cargo spill occurring every 65 years.
- One cargo fire occurring every 221 years.

7. Prevention and control

Restricting hazardous materials fully is not always feasible. However, restricting materials like flammable liquids or combustible solids may effectively prevent significant fires in heavily traveled tunnels. Furthermore, prohibiting hazardous materials during peak traffic periods, or periods when the drainage systems are handling large quantities of liquid of any kind has the advantage of reducing saturation of the drainage and sump storage systems at a time when they might be needed to remove spilled flammable liquids.

Controls on drivers' actions reduce the frequency of accidents, their resulting ignitions and possible impediments to fire fighting and life support systems. For instance, reduced speed limits create greater awareness of a dange·ous environment requiring greater care and help drivers control the vehicle.

The frequency of accidents in tunnels could be reduced considerably by prohibiting lane changing. Mere restriction of hazardous materials and controls on drivers' actions will be ineffective unless accompanied by vigorous enforcement actions such as:

- Portal inspections to identify placarded vehicles carrying restricted materials or unplacarded vehicles suspected of doing so.
- Stationing tunnel personnel to identify violators and either issue citations at the scene or notify constant authority for their follow-up is essential if either restrictions or controls are to be complied with.

Traffic safety could be greatly enhanced by several roadway features, thus reducing the frequency of accidents and ignition sources. These include:

- Gradual rather than sharp curves in the tunnel and its approaches.
- Lack of transition points such as exits or interchanges in the tunnel or its portal.
- Effective lighting at the portals and within tunnels.
- Interstate-standard lanes and overhead clearances for better visibility and emergency access.

When attempts at prevention are unsuccessful and fire starts, the next step toward control is detection. In the past, personnel stationed in the tunnels to monitor traffic have detected numerous fires. T.V. cameras are an effective substitution for personnel. Doppler radar systems may prove to be effective in controlling the traffic flow. High technology systems obviously require the use of computers, and computer-based control of all tunnel systems will eventually become the norm.

The second step in effective control is of alarm systems. Rapid transmission of alarms from fire scene to proper authorities enhances their effectiveness. Some systems include emergency telephones, which should be clearly marked, accompanied by simple operating instructions with care being taken to ensure the caller's message can be understood in a noisy tunnel. Fire alarm pull boxes should be located beside each telephone.

Once the fire is detected and necessary alarms transmitted, quick response in bringing limited control and available extinguishment systems is essential if minor fires are to be contained and rescue efforts successful. This requires planning and training and a fire/emergency plan, close liaison with local fire departments, and appropriate tunnel-owned equipment. Quick response and maximum reliance on drivers in the tunnel have always proven effective in tunnel fire control, with the help of fire extinguishers. The effectiveness of fire extinguishers depends on parameters like type, weight, spacing, positioning, familiarity, and security.

Although not often used, firelines and hydrants or hoses are also a common fire control system in tunnels. However, if the fire intensity is high, the water line to hydrants may suffer too much damage. Their effectiveness depends on capacity, compatibility, survivability, and freeze protection.

Notification systems, including traffic lights, signs, AM radio broadcasts, CB radio capability, etc., may serve as good means of control.

Damage and fatalities could be considerably reduced by means of proper ventilation to maintain a clear atmosphere within a tunnel. No specific criteria regarding components, arrangements, or modes of operation exist to guide tunnel designers toward a ventilation system that would enhance life safety, reduce damage, and facilitate control efforts during a fire emergency. The different types of ventilation systems include reversible, semi-transverse, supply-only ventilation systems and fully transverse systems. The design recommended for future ventilation systems on highway tunnels should include provisions for a smoke-extracted fire emergency mode employing motorized dampers in large ceiling exhaust ports approximately 300 ft (91.5 m) on center.

Use of well-designed lighting systems reduces accidents and ignition sources. However, once a major hazardous material fire is started, normal lighting has little effect.

Because of their long successful history, sprinkler systems are highly regarded by fire protection professionals and fire departments. Nonetheless, it does <u>not</u> appear that sprinklers are an effective fire control system in vehicular tunnels. The Nihonzaka fire (a major tunnel fire in Japan) study results indicated a thin spray on a very hot fire can produce large quantities of superheated steam without materially suppressing the fire. A sprinkler system that does not aggravate the fire, nor impair control and rescue, should conform to several design criteria.

Because water supply is an integral part of a complete fire prevention and control system, where possible, tunnel stand pipes should be connected to, or, in the case of dry pipes be connectable to, municipal water systems. Adequate drainage is also important for fire prevention and control.

Full-scale fire tests in a highway tunnel need to be performed to learn more about the behavior of heat and smoke and the effectiveness of some ventilation systems. Further study needs to be done to better estimate the risk and assess methods of prevention, detection, alarm, notification, control, and suppression.

IV. INFORMATION ON AUTOMATIC DETECTION AND COMMUNICATION SYSTEMS WITH POTENTIAL FOR ADAPTING TO HIGHWAYS

A. An Overview of Needs and Resources of Aerometric Instrumentation at Hazardous Spill Sites[29]

This chapter introduces spill sensors used to monitor locations where incidents would cause catastrophic consequences. Following chapters present specific examples of appropriate types of sensors for site-specific incidents. There is little or no history of their use in highway incident scenarios, so no literature or case studies can be cited. This is a new concept, and innovation must be used to adapt these types of detectors. Manufacturers and dealers with expertise should be contacted for the details of application to specific scenarios.

The current state of the art of ambient chemical instrumentation and meterological sensors offers many possibilities for improving the ability of response teams to predict the intensity and location of dangerous substances. These instruments are not normally used as permanent devices installed within highway systems, but they could be adapted for specific, high-catastrophic potential scenarios where quick warning would mitigate consequences. A program of research and development would most likely be necessary. Figures 30 and figure 31 show schematic diagrams of the system.

1. Time frame

Time can be a factor in several ways, but basically there is a need to consider what monitoring resources can be employed in each of the three logical phases of an incident. Phase 1 is the initial period of response, lasting from 2 to 8 hours and usually involving local responders. The principal object is to evaluate the emergency, contain it as much as is practical, and prevent injury to workers and nearby population. Phase 1 instrumentation will of necessity be restricted to widely available devices easily used by first responders. Phase 2 is the mature period of the incident and may last up to several days for major emergencies. Time is available to bring specialties and sophisticated hardware to the scene. Phase 2 concludes when the emergency is controlled. Phase 3 may last several weeks and focuses on the restoration of the site. The purpose of monitoring during this phase is to assess potential residual effects that may involve long-term hazards.

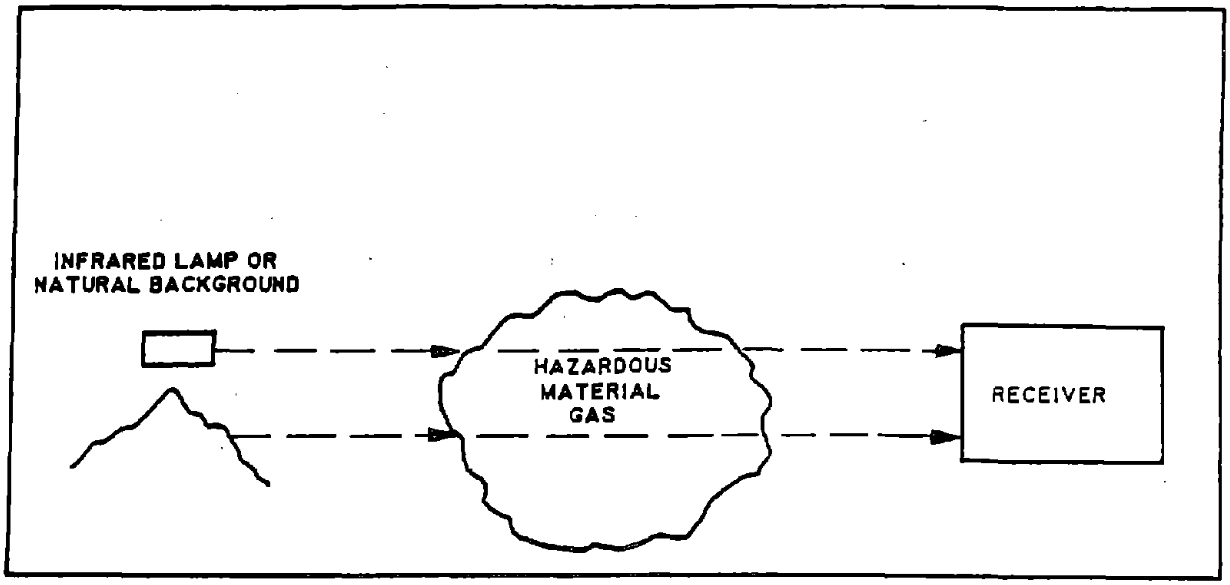


Figure 30. Geometry of the system.[29]

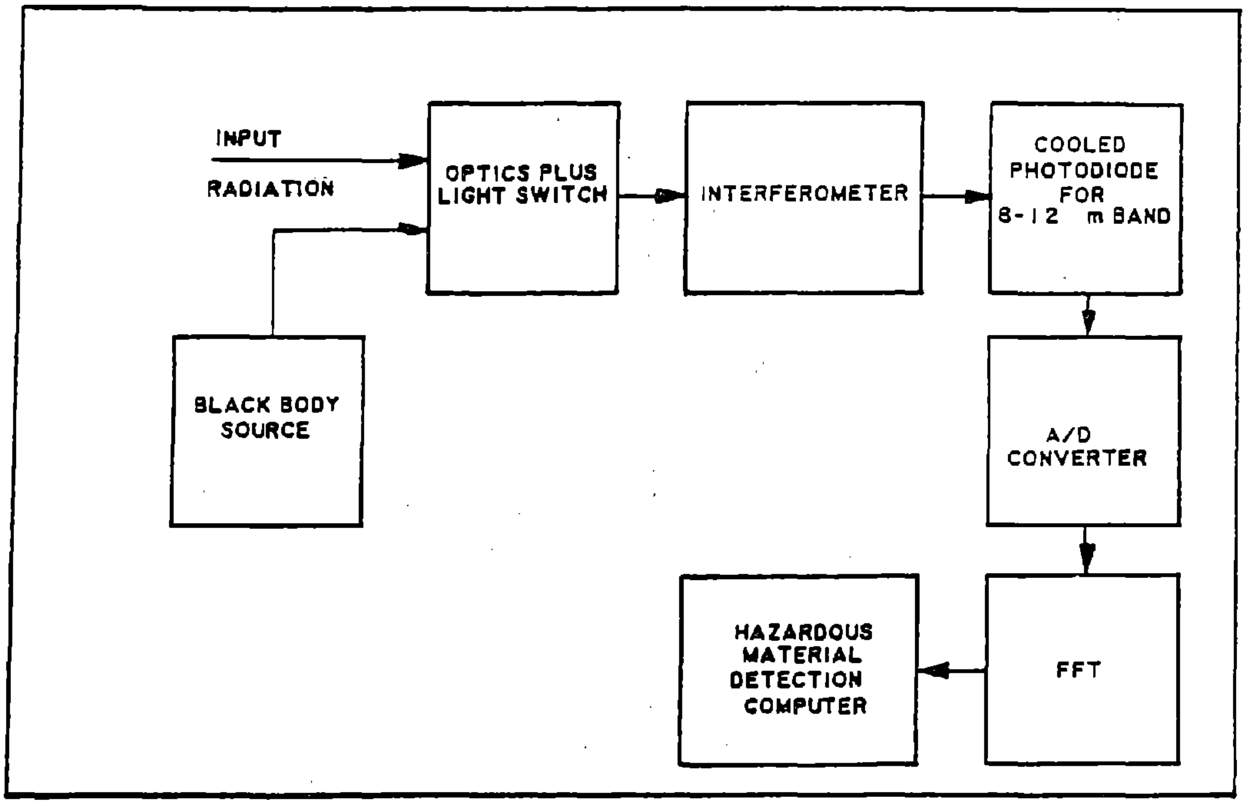


Figure 31. Block diagram of the system.[29]

The majority of highway related hazmat spills last only a few hours and would be classified phase 1. The main purpose, then, of a highway department deploying a detection device protective system within the highway is to quickly alert appropriate emergency response personnel to prevent catastrophic consequences. The State Department of Transportation should be in close contact with State emergency response personnel in the planning phase of these detection devices. Phase 2 and phase 3 hazards are the concern of response agencies.

There are at least two ways to match the needs of the responders and the capabilities of the measuring devices.

a. Individual instruments that are potentially useful can be reviewed, with the most promising candidates evaluated and ultimately used by the responders. This approach focuses on the advantages of the individual instruments but suffers from its failure to address the specific needs of the responders in a systematic way.

b. The various needs of the responders (as a function of time and personnel available and the nature of chemicals and affected groups of people) can be quantified and stratified into a hierarchy of monitoring requirements to be reviewed and evaluated, then assembled into systems designed for one or more of the various categories of user needs. This approach has the advantage of being user-oriented but may suffer if other useful, available techniques fall outside of the user-needs categories.

The optimum approach follows the second method, but recognizes the particular advantages of promising candidate instruments and sensing techniques.

2. User needs and constraints

Types of instrumentation and other techniques used at a spill site are governed by four classes or sets of constraints and considerations: 1) the time frame available for response, 2) the nature of spill and substance involved, 3) expertise of the responders, and 4) the spatial extent of the impacted area.

Spanning each of the four sets is the effect of the existing meterological conditions and the way in which they may change with time or location.

3. Nature of spill

The hardware used to monitor in each of the three phases is a function of the nature of the primary or secondary contaminants. Because the list of hazardous substances is so large, a priority listing needs to be prepared and appropriate methods considered according to the priority of the substance and the potential for obtaining a sensor to serve in the field.

4. Spatial extent

Monitoring requirements for emergency situations vary with the spatial aspects of the problem. Conditions immediately adjacent to the accident may necessitate different instrumentation from that used to assess the extent of the public evacuation zone further downwind. At the accident site, concentrations are apt to vary rapidly in time and space, requiring the use of one or more continuous or near-continuous sensors to protect workers. Further downwind, harmful secondary products may form that do not exist at the accident site or ambient level and may need to be monitored to assess the likelihood of chronic effects on unprotected people.

5. User expertise

The personnel available to operate the instrumentation is a major consideration in the selection process. Local first responders will often be unable to afford and operate the more sophisticated hardware. Accordingly, Phase 1 hardware will need to allow these users to assess whether the concentrations are hazardous. It will need to be relatively inexpensive, readily available, and easy to use properly.

6. Accident scenarios

Taken together, the above four classes of constraints--time frame, spatial extent, nature of spill, and user expertise--define most accident scenarios and the associated aerometric instrumentation requirements; monitoring devices and systems should be developed in the context of an integrated plan that recognizes the scope of the physical problem and the specific needs of the users.

7. Examples of available resources

A wide range of sampling and detection techniques are available for monitoring gases and aerosols for meterological measurements. This is the range of resources potentially available to support the air-monitoring needs of the emergency response teams.

a. Grab samples. Instrumentations for grab samples can vary from substance-specific detector tubes to highly sophisticated interferometers and gas chromatographmass spectrometers. Draeger tubes, for example, are well suited for a first-on-the-scene responder or a Phase 1 response team.

More sophisticated instruments such as portable infrared (IR) or portable gas chromatograph systems (GCS) or photoionization detectors offer more specificity and sensitivity of detection but are less portable and more complex to operate. For extremely toxic materials, more complex instrumentation such as IR interferometers, GCS with sensitive, specific detectors, and mass spectrometers can be used. These sophisticated instruments can be installed in vehicles to provide some portability, but only at a considerable expense and difficulty.

b. Remote sensing. One problem facing the emergency response team when hazardous gases are released into the atmosphere is defining the size and concentration of the plume. Surveillance of the plume is needed as soon as possible after the accident until effects are residual from the contamination of soil and water. Definition of the plume is also critical when actions such as increasing the release rate or confining the material are contemplated. In addition, the plume may be laden with toxic aerosols, or aerosols may form downwind. Remote sensing, because of wide area coverage, offers a way of defining these gas and aerosol plumes.

The diversity of remote sensing instrumentation is wide; however, these instruments may be classified in a simple four-parameter tabulation: 1) active or passive, 2) range-resolved or range-averaged, 3) airborne or ground-based, and 4) material specific or nonspecific. Remote sensing could be of particular value when spills involve highly toxic materials or when toxic materials are combusted after the accident. Mapping can be accomplished at hazardous locations without the risks involved with grab sampling.

c. Artificial tracers. Artificial, gaseous tracers can be injected into the hazardous spill at a known rate to provide at least four types of useful information:

- Definition of the distribution of toxic gases and their dispersion by acting as a surrogate for the gases of concern.
- Estimation of the actual concentration of the toxic gases, provided the rate of release of the toxic gases can be estimated.
- Estimation of the rate of release of the toxic gases, provided simultaneous ambient measurements of the tracer gas and the toxic gases at one or more representative locations.
- Real-time evaluation of atmospheric dispersion models; with the tracer data to provide an objective measure of confidence, the models can be used for real-time, on-site contingency planning.

Tracer gases such as sulfur hexafluoride at concentrations as low as 10^{-11} and grab sampling and batch analysis can provide reliable measurements to 10^{-12}. Active remote sensing systems for SF_6 that use infrared differential absorption principles are now being developed.

d. Meteorological data. Meterological data are available from the National Weather Service; however, surface and upper air weather data, available by teletype, can be obtained at the accident site most easily via telephone or terminal access to one of several private companies offering this service around the clock.

Microscale or local effects dominate the observed weather conditions at the accident site, particularly when dispersion conditions are poorest. Local meteorological measurements are a necessity. These should include wind measurements at multiple heights and different locations, particularly when the terrain is hilly or the area heavily forecasted. Temperature stratification near the ground is also important to assess air drainage patterns and the rate of diffusion of the toxic plume.

B. Remote Sensing and Special On-Site Techniques for Detection of Toxic Substrates[30]

1. Introduction

An accidental release of a material is usually a localized incident in which initial concentrations are highly variable in space and time. In later phases, the initial chemical or secondary products may be transported downwind. In every late phase, long-term monitoring may be needed to study the residual effects.

Remote sensing is the process of deriving information about a phenomenon or object without direct access for sampling. In an accidental release of a toxic substance, the phenomenon is a cloud of gas or aerosol not initially involved with the release. In such case, remote sensing can be used to give real data on cloud structures so the toxic release response can be better managed by the on-site team.

The use of remote sensing in highway situations would be limited to specific materials in specific situations with definite catastrophic potential. For example, in a location with a chance for the release of a highly toxic gas into a highly populated area, it would trigger automatic warning devices to speed evacuation. Such a location might be a depressed freeway in a heavily urbanized area.

2. General characteristics of a remote sensor

The characteristics of an electro-magnetic radiation at optical frequencies change while passing through or emanating from the region of a toxic cloud. The light may be natural or from a source such as laser. Observations of natural and artificial light (laser) sources are termed passive and active remote sensing, respectively. Additionally, the systems can be range averaged or range resolved. Range-averaged methods give the average concentration of a gas along the line of sight and range-resolved methods profile the gas cloud concentration over the range. Passive remote sensors give range-averaged results whereas certain laser radar (lidar) systems give range-resolved results. Lidar is an acronym for light detection and ranging.

A toxic gas cloud modifies the spectrum light passing through or emanating from it. The amount of emission is proportional to the quantity of material and the temperature difference between it and the surrounding atmosphere.

The average gas present can be determined by measuring transmission through the cloud with the equation

$$\ln(I/I_0) = \exp - \alpha c \ell, \tag{18}$$

where $I_0 \rightarrow$ initial intensity, $I \rightarrow$ the transmitted intensity, $\alpha \rightarrow$ the absorption coefficient, $c \rightarrow$ the concentration, and $l \rightarrow$ the path length.

3. Principles of operation of passive remote sensors

Passive sensing techniques involve measurement of infrared (IR), ultraviolet (UV) or visible radiation emanating from or through a toxic gas cloud. UV and visible radiation techniques are applicable during the day, affected by aerosols (haze) and fog.

The absorption or emission spectrum is usually derived in one of four ways:

- Using a diffraction grating.
- Using a Michelson interferometer (the most productive method).
- Using a filter in front of the lens.
- Comparing the spectrum to a reference measurement.

The United States EPA's Remote Optical Spectrometer for Emissions (ROSE) is an example of a Michelson interferometer. It is designed to cover the 8- to 14-micron atmospheric window where many hazardous materials either absorb or emit.

Once a spectrum scene is obtained by a Michelson interferometer, it can be stored as a background spectrum. Succeeding spectra can be compared against stored spectra. Any advection of gas or aerosols into the field of view will be manifested as identifiable features. Time series analysis of spectra can be used to alert an operator that a gas cloud is present.

A correlation spectrometer is another type of a well-developed passive instrument. Commercial examples are COSPEC (for SO_2 or NO_2) and GASPEC (for CO, HCL, and C_2H_6) both manufactured by Barringer Research, and the PLUMETRAKER (for SO_2 and NO_2) and GASPILS (for CH_4 and C_2H_6), both manufactured by Moniteg. Details on how these instruments function is best obtained from the manufacturer.

4. Thermal sensing

Passive sensors operating in the IR spectral region have extra benefits for the toxic spills management problem. Because they receive thermal radiation from a scene, they can be used to locate fires and other hot spots. Otherwise, a fire can be obscured from smoke and debris. Such systems are small, compact, and available from AGA Thermovision, Inframetrics, and Hughes Aircraft Inc. Other passive gas-sensing concepts include passive heterodyne radiometry, filtered vidicons, and filtered cameras. Filtered vidicons (TV cameras) and filtered film cameras have been used as remote imaging sensors of gases.

5. Active systems

Active systems always use an artificial light source to probe the cloud of interest. Normally this light source is a laser. Lasers can be constructed in a variety of ways to provide the spectral diversity important to absorption measurements. In addition, pulse lasers can provide range information. Distance is determined by measuring the time it takes to travel from the transmitter to the target and back to the receiver located inside the transmitter. The target can be a convenient reflector such as a building, side of a hill, or the terrain.

Two examples of the active system are the particulate backscatter lidar and differential absorption lidar (DIAL). A particular backscatter lidar is SRI International's Airborne Plume and Haze Analyzer (ALPHA-1). This system is mounted in a twin engine aircraft and can routinely survey large areas at speeds of up to 186.3 mi/h (300 km/h).

An example of the differential absorption lidar is SRI's DIAL system, helpful for measuring concentrations of SO_2, O_3, and NO_2. It can measure concentrations as low as 25 ppb SO_2 over a 1.86 mi (3 km) range using large cell sizes of 656 ft (200 m). The information provided by DIAL in this case would replace at least 1,000 conventional point sensors. IR DIAL systems have been used to measure a variety of gases such as ammonia, benzene, butadine, CO_2, Freon, Methanol, Ozone, Perchlorethylene, SO_2, Trichloroethylene, etc. (see table 17).

6. Special on-site techniques

A trace gas can be used to tackle the problems from toxic gases. Trace techniques applied to accidental toxic release problems can be used to determine two very important quantities: 1) they can determine the concentration of the toxic substance at a particular downwind distance, and 2) they can find the toxic substance source strength.

The relationship between toxic and trace gases can be expressed as:

$$X_A/Q_A = X_T/Q_T, \qquad (19)$$

where:

X_A = accidental toxic gas concentration (g.m^3);

Q_A = accidental toxic gas source strength (g/s);

X_T = tracer gas concentration (g/m^3); and

Q_T = tracer gas source strength (g/s).

Table 17. Dial system sensitivities to selected gases using a CO_2 laser.[30]

Species: Name	Species: Formula	Absorption Coefficient (cm^{-1} atm^{-1})	Sensitivity (ppb-km)
Ammonia	NH_3	120.0	0.42
Benzene	C_6H_6	2.3	22.
1,3 butadiene		3.45	15.
Carbon dioxide	CO_2	1.8 (10^{-3})	28000.
Ethylene	C_2H_4	33.0	1.5
Freon 113	$C_2Cl_3F_3$	19.2	2.6
Freon 11	CCl_3F	31.0	1.6
Freon 12	CCl_2F_2	92.0	0.55
Methanol	CH_3OH	19.4	2.6
Ozone	O_3	12.7	4.0
Perchloroethylene	C_2Cl_4	28.5	1.8
Sulfur dioxide	SO_2	6.73	7.5
Sulfur hexafluoride	SF_6	800.0	0.063
Trichloroethylene	C_2HCl_3	14.0	3.6
Vinyl choride	C_2H_3Cl	6.79	7.4
Water vapor	H_2O	0.36 (10^{-4})	60000.

The source strength of the toxic gas is: $Q_A = X_A Q_T/X_T$, and the concentration of the toxic gas elsewhere is: $X_A' = X_T' Q_A/Q_T$, where X_T is the measurement of the tracer concentration elsewhere.

Popular tracer materials include freons, sulfur hexafluoride (SF_6), perfluorocarbons, deuteranted methane, fluorescent particles, and smokes. For example, a commonly used tracer gas is SF_6. The detection limit for SF_6 is 1 ppts (one part in 10^{12} by volume) using gas-chromatography with an election capture detector. Nominal release rates of 50/h have been used in flume studies at a cost of approximately $10/kg. Concentrations on the order of 100 ppb to 31.1 mi (50 km) were encountered downwind, depending on conditions.

C. Non-Remote Sensing Techniques[31]

The non-remote sensing field has a number of available instruments, including several commercial instruments using radiation absorption techniques: infrared (IR), ultraviolet (UV) and visible mass spectrometry; gas chromatography; gas chromatography/mass spectrometry (GC/MS); and specific material chemical reactions and parameter measurement techniques (PH, conductivity, colorimetric indicators, gas and vapor detectors). The GC/MS and dispersive IR analyzer show promise for near-term development. However, methods for detecting specific materials presently appear the most practical and broadly applicable for accident site use. These include specific colorimetric detector tubes, water analysis kits, gas and vapor detectors, and dosimeters.

These detectors are most applicable to use by emergency responders evaluating an incident. They would have to be adapted for installation or a permanent protection system warning device at a specific location. Their use would be limited to highly sensitive populations and consquences with high catastrophic potential.

1. Colorimetric Indicators

Detector tubes are a type of visual colorimetric indicator comprised of a sealed glass cylinder with chemically dilated packings designed to react with a specific gas or vapor. Typically, a calibrated pump is used to draw a vapor sample through the tube, then length of strain or degree of color changes is determined from calibration charts. This method can be applied to the following: acetone, acrylonitrile, anhydrous ammonia, butadine, chlorine, ethylene oxide, anhydrous hydrozine, hydrochloric acid, liquified hydrogen, methyl alcohol, nitrogen oxides, propane, propylene toluene, etc. The indicators are manufactured by Mine Safety Appliances Company (MSA), National Draeger, Inc., Bendix/Gastee (National Environmental Instruments, Inc.) and Matheson Gas Products (Division of Hill Ross, Inc.).

One shortcoming is that these indicators/detectors are generally material specific and of very limited use for identifications of unknowns or mixtures, which is the usual case in accidents. However, where the presence of a material is suspected, these indicators might help verification.

2. <u>Water analysis kits</u>

Several kits have been developed for analysis of hazardous materials in water. The two major types differ basically in the nature of the tests involved. One uses non-specific chemical class tests for detection of pollutant presence, and the other key tests for specific contaminant identification. The first type of kit is commercially available from HAC Chemical Co., while the second is still under evaluation by EPA. The problem with both is that training is required to perform and interpret results.

3. <u>Gas and vapor detectors</u>

Many different vapor detectors are available for different applications and varying levels of sensitivity. There are instruments to measure concentrations in percent by volume or percent lower explosive limit (LEL); instruments for specific ranges of explosives; instruments for a broad range of combustibles; and instruments which do not depend on combustion for their operation.

CEA Instruments, Inc., sells a portable continuous colorimetric analyzer capable of detecting ammonia, chlorine, hydrazine, methlylhydrazine, and oxides of nitrogen.

The combustion type devices are widely used by emergency response groups for monitoring flammable or explosive atmospheres associated with an accident site. They are portable, relatively inexpensive, and require little technical training to use. Several modes are available, including the MSA Explosimeter, the Grace Industrial Electronic Nose, the Bacharach TLV Sniffer, Infrared Industries Portable Hydrocarbon Analyzer, and the Scott/Davis Portable Flame Ionization Meter.

4. <u>Dosimeters, personal monitors, alarms</u>

These instruments help indicate danger level of exposure for individuals in the vicinity of hazardous materials releases. They may be the portable alarms designed to respond to a specific material such as the U.S. Army M43 alarm, which responds to nerve agents, and monitors used in mines and tunnels, or personal monitors like the Dupont Pro-Tek badges for toxic gases, available for use by emergency responders. MDA Scientific, Inc., produces personal pocket-sized monitor/alarm units which monitor ammonia, chlorine, hydrazines, and NO_2. However, these units are specific to a given material.

A large number of instruments are commercially available for specific applications during hazardous material emergencies, but none for identifying an unknown material.

Table 18 gives a summary of appropriate HM identification methods for several chemicals and propellants.

Table 18. Summary of appropriate hazardous materials identification methods for chemicals and propellants.[1]

Material	Service Stenciling	Colorimetric Indicator	Dosimeters, Personal Monitors, Alarms	Gas Detector
1. Acetone		*		*
2. Acetone Cyanchydrin				
3. Acrylonitrile		*		*
4. Aerozine-50				
5. Anhydrous Ammonia	*	*	*	*
6. Butadiene, Inhibited	*	*		*
7. Chlorine	*	*	*	*
8. Ethyl Acrylate, Inhibited				
9. Ethylene Oxide		*		*
10. Hydrazine, Anhydrous		*	*	*
11. Hydrocyanic Acid		*		*
12. Hydrogen, Liquefied		*		
13. Isobutane (LPG)				*
14. Methyl Alcohol		*		*
15. Methyl Bromide		*		*
16. Methylhydrazine		*	*	
17. Monomethylamine Nitrate				
18. Nitrogen Tetroxide, Liquid		*	*	*
19. Oxygen, Pressurized Liquid		*		
20. Propane (LPG)	*	*		*
21. Propylene (LPG)		*		*
22. Sodium Hydrosulfide Solution				
23. Sodium Hydroxide Solution				
24. Styrene Monomer, Inhibited		*		*
25. Toluene		*		*
26. Dimethylhdrazine Unsymmetrical		*	*	*
27. Vinyl Acetate		*		
28. Vinyl Chloride		*		*

[1]This information is taken from manufacturers' literature. Refer to SRI Dictionary of Chemical Procedures for listing of chemical manufacturers in your area.

APPENDIX A. PROCEDURES FOR ESTABLISHING TRUCK ACCIDENT RATES AND RELEASE PROBABILITIES FOR USE IN ROUTING STUDIES[3]

Several procedures can be used by highway agencies to develop default truck accident rates and release probabilities from their own data to replace the default values in table 13. While the use of site-specific accident data for two particular alternative routes being evaluated is discouraged, except where there is a need, estimates of truck accident rates and release probabilities based on an agency's own data are preferred to the use of the default estimates in table 13.

The following discussion identifies the data required for an agency to develop these estimates and the data processing procedures that should be used.

A. Data Needs

Three types of data are needed to estimate truck accident rates and release probabilities in a form useful for hazmat routing analyses. These are:

- Highway geometric data.
- Truck volume data.
- Truck accident data.

For the analysis to be accomplished efficiently, this data should be available in computerized form using a common location identifier (e.g., mileposts) so the three types of data can be linked together. Many State highway agencies have been computerized and linking their data files and now, or soon will, have the capability to perform this type of analysis.

We are not aware of any State that currently has the necessary data and linking capability to analyze all public highways under the jurisdiction of the State highway agency. To obtain unbiased estimates, the highway geometric, truck volume, and truck accident files should cover the entire State highway system. If only a subset of the State highway system is used, this subset should be selected through a statistical sampling process to maintain the unbiased nature of the estimates.

Highway geometric files are needed to define the characteristics of segments to which truck volume and accident data can be added. Highway geometric files typically consist of relatively short route segments (0.35 mi [0.56 km] or less in length) for which data on the geometric features of the segment is included. The minimum data that should be available for this analysis is:

- Number of lanes.
- Divided/undivided.
- Access control (freeway/nonfreeway).
- One-way/two-way.
- Urban/rural.

Other data typically available in highway geometric files users might want to consider include lane width and shoulder width. In addition to roadway segment data, geometric files often include records of the geometrics of individual intersections and freeway ramps. These features could be considered in the development of default accident rates.

Traffic volume files typically include the Annual Average Daily Traffic (AADT) and may also include either the average daily truck volume or the percent of trucks in the traffic stream. To be useful, truck volume data needs to be given in the same location reference system as the highway geometric and accident data.

The truck accident data needed for the analysis is a subset of the accident files for all vehicle types maintained by all State highway agencies. In selecting accidents for inclusion in the analysis, it is important to use the same definition of a truck used in obtaining the truck volume counts. Because nearly 80 percent of the accidents in which hazardous materials are released involve combination trucks (i.e., tractor-trailers), it would be desirable to limit the accident analysis to combination trucks only. Unfortunately, however, truck volume data for combination trucks are seldom available on a system-wide basis. Therefore, it is often necessary to use truck volume data and accident data for all trucks or for all commercial vehicles. Traffic counts for "all commercial vehicles" typically include both trucks and buses. Thus, when traffic volume counts for "all commercial vehicles" are used, it is important to include both bus and truck accidents in the analysis.

Typical accident characteristics that should be included in the analysis are:

- Number of vehicles involved.
- Types of vehicles involved.
- Type of collision (if any).

- Date of accident.
- Accident severity (most severe injury).

Each accident-involved vehicle should be treated as a separate observation (i.e., an accident involving two trucks should be counted as two accident involvements).

B. Data Processing

Five steps in processing the data described above are illustated in figure 32. This processing can be accomplished using a standard statistical package such as the Statistical Analysis System (SAS). The key element is linking the appropriate truck volume and accident data to individual roadway segments from the highway geoemtric file using a common location reference system (e.g., mileposts). Each step in linking the data from these files is described below.

1. The data for the individual roadway segment should be read from the highway geometric file. Only those geometric data items needed for the analysis should be read (see example list given above). The highway class (highway type and area type) of each roadway segment should define based on the available data. Typical highway classes include:
   - Rural two-lane highways.
   - Rural multilane undivided highways.
   - Rural multilane divided highways.
   - Rural freeways.
   - Urban two-lane streets.
   - Urban multilane undivided streets.
   - Urban multilane divided streets.
   - Urban one-way streets.
   - Urban freeways.
2. Individual roadway segments, with relatively short average lengths, should be merged into longer segments when adjacent segments match in highway class and other selected variables and when have average daily traffic volumes within 20 percent of one another. When adjacent highway segments are merged, their average daily traffic volumes should be combined using a weighted average by length, as follows:

$$ADT_c = \frac{ADT_1 L_1 + ADT_2 L_2}{L_1 + L_2} \qquad (20)$$

(Intentionally left blank)

where: ADT_c = average daily traffic volume for combined segments;

ADT_i = average daily traffic for route segment i;

L_i = length (mi) for route segment i.

3. Any roadway segments without available accident or truck volume data or which did not fit, should be eliminated.
4. The truck volumes for the merged sections should be obtained from the volume file. The truck volume data should be used, with the length of the segment, to compute the annual veh-mi of truck travel on each segment:

$$TVMT_i = TADT_i \times L_i \times 365 \tag{21}$$

where: $TVMT_i$ = Annual truck travel (veh-mi) on route segment i; and

$TADT_i$ = Average daily truck volume (veh/day) on route segment i

5. Data on truck accidents should be obtained from the accident files. Each truck accident involvement should be classified by year, accident severity, and accident type. The common location reference system used to link the accident and geometric files should be used to decide which segment the reported location of each accident falls within and to total the number of accident type. Each year of data for each segment should generally be treated as a separate observation in the analysis.

The results of step 5 is a file containing the truck volumes and truck accident histories for individual highway segments that can be used to compute truck accident rates and release probabilities.

C. Data Analysis

The average truck accident rate for each highway class can be computed as the ratio of total truck accidents to total veh-mi of truck travel for that highway class. In other words:

$$TAR_j = \frac{A_{ij}}{VMT_{ij}} \tag{22}$$

where: TAR_j = Average truck accident rate for highway class J;

A_{ij} = Number of accidents in 1 year on route segment i in highway class j; and

VMT_{ij} = Annual veh-mi of travel on route segment i in highway class j.

The values of TAR_j for each highway class from equation (23) can be used to replace the default truck accident rates in table 13 with values more suited to local conditions.

The probability of a hazmat release given an accident varies between highway types because it varies with accident type and because the distribution of accident types varies markedly between highway classes. For each accident involved truck, the FHWA motor carrier accident reports determine both whether the truck was carrying hazardous materials and whether the hazardous materials were released. Only three States currently have both data items needed to make this determination in their accident records systems.

The probability of a release given an accident involving a hazmat-carrying vehicle can be computed as:

$$P(R|A)_j = \sum_k P(R|A)_k \times P(k)_j \tag{23}$$

where: $P(R|A)_j$ = Probability of a hazmat release given an accident involving an hazmat carrying vehicle for highway class j;

$P(R|A)_k$ = Probability of a hazmat release given an accident involving a hazmat carrying vehicle for accident type k; and

$P(k)_j$ = Probability that an accident on highway class j will be of accident type k (i.e., proportion of truck accidents for each accident type highway class j from State accident data).

The values of $P(R|A)_j$ from equation (23) can be used to replace the default values for the probability of release given an accident presented in table 13.

APPENDIX B. SUMMARY OF THE DANGEROUS GOODS TRUCK ROUTE SCREENING METHOD FOR CANADIAN MUNICIPALITIES[32]

A. Introduction

The route screening method generates a short list of candidate routes for detailed study. Identifying routes that are safer than others involves a complicated time-consuming and expensive evaluation of each route alternative. Therefore, the focus of attention may be on candidate routes likely to provide the greatest safety. Focusing on a few reasonable routes would reduce the commitment of funds by eliminating options with little chance of satisfying the need for safety.

The method was developed to be easily workable by a non-technical user, to account for the 24 divisions (Canadian classifications) of dangerous goods in very general terms as well as to permit users to assess single commodities.

The route screening method addressed the question of reducing risks through careful selection of routes. At its highest level of analysis it is very similar to the FHWA routing method.[1]

A number of factors combine to determine the actual risk of dangerous goods transportation by road, and some of the factors relate to the probability of a dangerous goods incidence. In the same way, a number of factors influence the actual effects of a dangerous goods incident.

The adopted method accounts for five principal factors in estimating risk that could reasonably be associated with a release of dangerous goods:

- Accident probability.
- Potential consequences to populations.
- Potential consequences to property.
- Potential consequences to the environment.
- Response capability.

The consequence measures are generally additive, which assumes an observer would have more concern for an incident in an area that was both heavily populated and environmentally sensitive. Response capability is the only measure that reduces risk by its presence. Although increased capability does not alter the probability of an incident, it can still play an important role in mitigating adverse effects in all three impact categories: population, property, and environment.

The risk equation, with an appropriate measure of response capability incorporated, is:

$$\text{RISK} = \begin{matrix}\text{Accident}\\ \text{Probability}\end{matrix} \times \left(\begin{matrix}\text{Population}\\ \text{Exposure}\end{matrix} + \begin{matrix}\text{Property}\\ \text{Exposure}\end{matrix} + \begin{matrix}\text{Environment}\\ \text{Exposure}\end{matrix}\right) + \left(\begin{matrix}\text{Response}\\ \text{Capability}\end{matrix}\right) \quad (24)$$

This is the general form of the risk equation eventually adopted for the Canadian route screening method.

B. Intended Users

Intended users include officials, managers, and technicians at the municipal level of government. The method is designed for persons with little or no knowledge of dangerous goods, risk analysis, or transportation planning. However, at least one member of the study team should have a working knowledge of algebra, and one team member should also be familiar with sources of transportation, land use, and population information within the community.

The method includes a measure of flexibility and can be easily adapted to different situations. This is because some communities may also be concerned with probability and population impacts, and the user may wish to quickly dispense with secondary issues such as property or environmental effects. Also, because the communities vary in size and available resources, the amount of detail they wish to get from the analysis may also vary.

C. Levels of Detail

The users of the method are given the choice of three levels of detail for each of the five factors. The simplest method, called detail level 1, uses major assumptions to quickly provide an estimate of risk. The simplest measure of probability, for example, assigns a general accident rate to roadway types based on national accident figures. This is most suitable for those who want only a general measure of probability.

In the detail level 2 analysis, a closer look at probability is given and related to historic accident data for the roadway in question, and an average accident rate is calculated for all routes of interest. The detail level 3 method simply follows the FHWA Routing Guide method, using the accident probability obtained from analytical model presented there.

A similar approach is used for the other four factors. Level 1 for each factor uses rough estimates from readily available data, whereas levels 2 and 3 use increasingly more detailed data and a more rigorous analysis.

Considering all five factors in the method results in 15 possible steps. The simplest approach is a look at the lowest possible detail, represented by detail level 1. The comprehensiveness of the evaluation within a given level increases by adding factors by moving downward in the figure. By moving to the right, users gain confidence in line evaluation results by considering certain (or all) factors in more detail.

Table 19. Levels of detail for risk factors.[31]

LEVELS OF DETAIL

	Level 1	Level 2	Level 3
Probability	______	______	______
Population	______	______	______
Property	______	______	______
Environment	______	______	______
Response Capability	______	______	______

The advantage of the level 1 evaluation is that it allows users with low budget or low interest in certain factors to deal with it quickly. If users are most concerned with population impacts and probability, and willing to invest in the detailed (level 3) evaluation to address these two issues, they may wish to preselect routes based on these two factors only and proceed quickly through the remaining factors using detail level 1 information only.

It must be emphasized that a level analysis is basically the same level of detail as that presented in the FHWA routing guidelines.[1]

D. Rounds

Another feature this approach provides is the ability to conduct the evaluation in rounds. This saves time researching thoroughly all route options, including risks that show little promise of providing safe routes.

In this approach, all options start with an equal rating, and a round of evaluation is applied at the simplest level of effort. To identify options that can be confidently retained as viable, the results of the first round are compared. The rounds continue on successive viable options from each previous round until options are clearly identified, users are clearly identified, or users are satisfied with the level of confidence the results provide. The process will quickly narrow the field to realistic options, and it can be stopped at any time when a reasonable number of options are selected.

This is essentially an overlay technique to screen unwanted options or, more accurately, to highlight options with the least favorable attributes. Although the method is not an absolute analysis, relative values are developed within the method to highlight route options that will likely result in minimal risk associated with transporting dangerous goods.

E. Route Options

A clearly delineated step is added to the route-screening method to account for many non-risk factors, such as physical restrictions along a roadway.

F. Accident Probability

The probability of an accident on a route segment is expressed as:

Probability = Accident Rate x Segment Length ($P = y \times L$). (25)

From the literature review (for the Canadian study) it was observed the dominant method is the FHWA Routing Guidelines (1980). The essential steps of this method are:

a. Determine the accident rate for all vehicles on a particular road segment.
b. Calculate the probability of an accident for any vehicle, based on vehicle exposure.
c. Factor the probability for any vehicle to reflect the incidence of dangerous goods vehicle accidents as a fraction of all accidents.

The general form is:

$$P = \frac{\text{Vehicle accidents}}{\text{veh-km}} \times \frac{\text{veh-km}}{\text{veh}} \times \frac{\text{dg}^5\ \text{acc}}{\text{all veh acc}} \qquad (26)$$

The probability for each of three roadway types--Interstate, urban arterial, and rural highway--are estimated using analytical accident prediction models.

[5]dg = dangerous goods; the common term in Canada and other countries for hazardous materials.

G. Population Exposure

A great number of factors help determine the actual effects of a dangerous goods release. The basic assumption is the more people exposed to a hazardous condition, the greater the potential for serious consequences. Exposure represents the number of people potentially threatened by a release of dangerous goods during transport as opposed to the number actually injured or killed.

The population exposure is measured by three methods in the workbook as the number of people assumed to be present within an impact corridor extending 1.61 mi (1 km) on both sides of a transport route. A total corridor width of 3.22 mi (2 km) represents the potential research of some of the more hazardous products such as poisonous gases or radioactive materials. Users of the method should adjust the impact corridor to suit their needs.

Detail level 1 enables users to quickly evaluate routes by applying general population density figures assigned to represent community types. The second level of detail calls community for land use information to help estimate population. The third level of detail resembles the approach suggested by Urbanek and Barber in 1980 FHWA Routing Guidelines. The Canadian level 3 is basically the same as the FHWA routing guide process. Detailed census tract information is used to estimate the total population within a hazardous area.

H. Property Exposure

The property values are given in terms of dollars per linear meter for eight land use categories. Building replacement costs are expressed in dollars/linear meter because it is generally thought dangerous goods releases (such as explosions) that could damage property would for the most part affect buildings fronting a roadway.

Three major methods are used to quantify property be exposed to dangerous goods release. The first makes use of land use types and assigns values based on inherent or assumed property values. A second and more reliable method is suggested by the FHWA Routing Guidelines and involves a quick survey of the occupancy types along the route options. The results are compared with actual property values established for the community. The third method accounts for special properties and facilities along the route options. The FHWA Routing

Guide suggests using weighted values to the community facilities that are sensitive to destruction.

I. Environment Exposure

Like the population and property components, environmental exposure is a measure of consequences of a dangerous goods occurrence. It accounts for the exposure of sensitive environments to dangerous goods releases. The general measures of environment exposure include hectares of marine waters, rivers, creeks, and wetlands exposed to dangerous substances along a given route. As a consequence factor, environment exposure can be used to help distinguish the relative safety of transporting dangerous goods by truck along any number of given routes.

Relatively few studies have considered environmental issues in connection with the transportation of dangerous goods in usable detail. Some studies have incorporated a concern for environmental protection directly in their methods. Part of the difficulty in identifying environmental resources is that they may be at some distances from the route. Spilled product has been known to travel along drainage courses to affect sensitive environmental areas more than a kilometer from the site of the spill. Groundwater reserves can also be affected at some distances from transport routes. Liquid products cause major concern when dealing with environmental issues because of their tendency to follow drainage courses away from accident sites.

The simplest evaluation method uses land use information to quickly estimate sensitive areas adjacent to potential routes. The Canadian manual used the Tera Method to suit the requirements of the screening approach.

J. Response Capability

The response capability considers the affect of available emergency services for reducing the effects of dangerous goods occurrences in truck transportation. It measures how the overall risk of transporting dangerous goods along a given route may be reduced through the intervention of fire service, police, and ambulance personnel. The response capability can evaluate in three levels of detail along a given route and favors routes (less risk) having a higher number of emergency response services per route length.

An estimation of response capability can be obtained from the number of fire companies trained and equipped for dangerous goods response available on a per unit basis along a given route. The response capability method prescribes that emergency services must be capable of responding to an occurrence anywhere along a given route within 10 minutes. A simple expression of response capability is:

$$\text{Response capability} = \frac{\text{Total number of Emergency Response units within 10 minutes}}{\text{Route length}} \qquad (27)$$

Detail level 1 considers the number of trained and equipped fire companies capable of responding to a dangerous goods incident anywhere along a given route within 10 minutes.

Detail level 2 integrates the number of police cars capable of responding along any given route within 10 minutes.

Detail level 3 adds the number of ambulance units available within 10 minutes along a given route for communities with a high interest in response capability for screening candidate dangerous goods routes.

K. Validation Tests

To determine whether the requirements of a screening method are feasible and practical, validation tests were conducted using real or fictitious transport routes and data. Specifically, data requirements for each risk factor and detail level were evaluated for consistency and practicality in using a screening method. One major finding of the validation test for population exposure was that the use of route segments was impractical and confusing, given the number of census tract boundaries likely to be found along a route option, and the use of route segments was dropped from the process. However, tests demonstrated that it is possible, given census tract information, to determine the total number of people exposed along a route option.

By estimating the distance of land uses along a given route, given the value of representative building replacement costs, the value of property exposed to dangerous goods in transport along a route can be determined.

The validation tests determined the requirements of the screening method were, for the most part, feasible and practical. The major finding of the validation process was that the overall method worked. Limitations of the method in terms of its practical application can be summarized by stating that the approach outlined in the Canadian workbook is essentially a guide and may seem restrictive in certain situations.

L. Product Hazards

Product hazard is, at the root of any problem, associated with the transportation of dangerous goods. A correlation exists between the hazards of products and the amount of risk involved in transporting dangerous goods: the greater the product hazard, the greater the risk. No accepted scientific and objective method is evident for rating the degree of hazard for each of the product categories. The principal requirement of product hazard in terms of a route-screening method is to distinguish divisions of dangerous goods in selecting transportation routes with the greatest potential for safety. There are a number of ways to measure product hazard.

The FHWA Routing Guidelines attempted to define potential impact areas by classes of dangerous goods in terms of distances likely to be affected by materials. The contractor used route segments 1/2 mi (.31 km) on each side of a route and 1-mi (.62 km) long to derive consequence subfactors which were figured additively for environment, population density, property, and storage. This was done separately for routes of all applicable transportation modes. Each of the routes was assigned a value of 0 to 25 by applying data to empirical charts and tables. The four subfactors were used additively, giving a range of 0 to 100 for total consequences subfactors. ABAG adopted a modification of this model.

APPENDIX C. SUMMARY OF EVACUATION DISTANCES OF SELECTED HAZARDOUS MATERIALS

The tables given in 1987 Emergency Response Guide Book for Hazardous Materials Incidents suggest distances for "isolating" or "evacuating" unprotected people from spill areas involving selected hazardous materials.[5] Maximum, minimum, and average values of all materials, along with a summary of class 2 gases were calculated and are presented in table 20 and table 21. Some important statistics are presented below.

The following points should be noted:

- The minimum Isolation Distance = 50 ft (0.0947 mi)[15.24 m, .152 km]. The minimum Evacuation Distance = 150 ft (0.0285 mi) [45.7 m, .046 km].
- All these 'selected' hazardous materials fall under Class 2..."Gases."
- For each class and division (e.g., Class 2, Division 2.3), the maximum, minimum, average, standard deviation of evacuation distance by division and by overall class were calculated.
- The calculations were also carried out for evacuation distance in the downwind direction.
- The total number of "selected" materials = 108.
- The number of materials in division 2.1 (flammable gases) = 23.
- The number of materials in division 2.3 (poison gases) = 77.
- The number of materials in division 2.4 (corrosive gases) = 8. The results are shown in table 20.

The same calculations for classification by class were broken out, and the results are tabulated in table 21.

Table 20. Evacuation distances classification by United Nation division.[1]

		Type of Gases		
		Flammable	Poison	Corrosive
1.	Maximum Evacuation Distance (miles) (in all directions)	0.11	0.227	0.114
2.	Minimum Evacuation Distance (miles) (in all directions)	0.0284	0.0284	0.0284
3.	Average Evacuation Distance (miles) (in all directions)	0.051	0.058	0.04
4.	Standard Deviation (miles)	0.0332	0.0457	0.0304
5.	Maximum Width (miles) (evacuation in downwind direction)	1.5	3	0.8
6.	Minimum Width (miles) (evacuation in downwind direction)	0.2	0.2	0.2
7.	Average Width (miles) (evacuation in downwind direction)	0.356	0.672	0.35
8.	Standard Deviation (miles) (evacuation in downward direction)	0.344	0.655	0.278
9.	Maximum Length (miles) (evacuation in downwind direction)	3	3	1.5
10.	Minimum Length (miles) (evacuation in downwind direction)	0.2	0.2	0.2
11.	Average Width (miles) (evacuation in downwind direction)	0.644	1.149	0.575
12.	Standard Deviation (miles) (evacuation in downwind direction)	0.716	1.030	0.578

[1]Data in these tables calculated by computerizing and summarizing data in reference 5.
1 mi = .621 km

Table 21. Energy of class 2 (gases).[1]

	Type	Class 2 Gases
1.	Maximum Evacuation Distance (in all directions)	0.227 mi
2.	Minimum Evacuation Distance (in all directions)	0.0284 mi
3.	Average of Evacuation Distance (in all directions)	0.055 mi
4.	Standard Deviation	0.0419 mi
5.	Maximum Width (downwind direction)	3 mi
6.	Minimum Width (downwind direction)	0.2 mi
7.	Average Width (downwind direction)	0.573 mi
8.	Standard Deviation	0.588 mi
9.	Maximum Length (downwind direction)	3 mi
10.	Minimum length (downwind direction)	0.2 mi
11.	Average length (downwind direction)	0.984 mi
12.	Standard Deviation	0.959 mi

[1]Data in these tables calculated by computerizing and summarizing data in reference 5.

APPENDIX D. EVACUATION DISTANCES DURING TOXIC AIR POLLUTION INCIDENTS[33]

The Emergency Response Unit of the Illinois Environmental Protection Agency (IEPA) has developed and successfully used calculations for evacuation distances during air pollution incidents with dispersion coefficients developed for three meterological weather stability classes.[33]

Calculation of maximum ground-level concentrations can be performed as follows:

$$X = Q/\pi\mu\sigma_y\sigma_z, \qquad (28)$$

where: X = concentration (gm/m^3);

Q = source strength (gm/s);

π = 3.14; μ = wind speed (m/s); and

σ = horizontal dispersion coefficient.

The practical application of this formula is based on the following assumptions:

- The material diffused is a stable gas or aerosol (less than 20 microns in diameter) that remains suspended in the air over long periods of time.
- None of the materials emitted is removed from the plume as it moves downwind and there is complete reflection at the ground.
- The plume constituents are distributed normally in both the horizontal and vertical directions.

An acute exposure safe level, or excursion threshold limit value (ETLV), has been developed by IEPA for approximately 500 toxic gases and vapors, chemicals selected from existing lists of hazardous substances.

ETLVs were established for two categories of toxic substances: severely toxic and moderately toxic. For severely toxic chemicals, the calculations are based on guarding the general population from the earliest easily defined clinical sign of toxic effects for a 1-hour acute exposure. For moderately toxic chemicals, the calculations are based on the principle from typical first level effects, such as irritation and narcosis.

Substances placed in the severely toxic and moderately toxic categories were determined by comparing their evaporation rates to critical evaporation rates for highly and moderately volatile substances.

The evaporation rate (E) for each substance is calculated by using the formula:

$$E = 0.0012 \times C \times \emptyset\ (760 - d\emptyset), \tag{29}$$

where: E = evaporation rate (gm/s - cm^2);

C = molecular weight of substance/28.9;

d = 1-C; and

Ø = vapor pressure (mm Hg at 20°C (68°F)).

Given the molecular weight and vapor pressure of a substance, we can calculate an evaporation rate comparable with the approximate critical evaporation rate. If the calculated evaporation rate is greater than the critical value, the substance should be assumed to be capable of exceeding the maximum allowable ambient concentration for that toxic substance category.

The maximum allowable concentration for the severely toxic category was determined to be 6.62×10^{-7} lbs/35.315 ft^3 (0.3 mg/m^3), based on a typical chlorine inhibitor, and that for the moderately toxic category was 200 mg/m^3, based on a typical irritants concentration known to cause that clinical symptom.

By using the above values and the ground-level Gaussian dispersion equation, the following critical evaporation rates were calculated:

6.3×10^{-8} gm/s-cm^2 for the moderately toxic category for the following conditions:

- Spill area = 600 ft^2 = 55.7 m^2.
- Stability category "F" (Stable).
- Windspeed = 3.28 ft/s (1 m/s).
- Receptor distance = (.0621 mi) 0.1 km.

An ETLV is the calculated outdoor ceiling level and is usually greater than the threshold limit value (TLV), but not always because the toxic effect must be considered. The type of toxic effects and of the levels needed to cause minimal health effects are the determining facts in setting ETLVs. ETLVs are expressed as milligrams per cubic meter and can be converted from parts per million (PPM) by the equation:

$$mg/m^3 = PPM \times MW/24, \tag{30}$$

where: MW is the molecular weight and 24 is a constant from the ideal gas law.

1. Determination of Q

The determination of gas to air is (air pollution): for a leak, Q = 1000 gm/s; for instantaneous discharge, Q = (Total lb/2.2) x density x 10^3 = gm.

For the spill of a volatile liquid to the ground (land, air, or possible water pollution): for a leak, Q = 3000 gm/s; for instantaneous discharge, Q = gal spilled x 3.8 x density x percentage of spill rate x 10^3 = gm.

The spill of volatile liquid into water and material is water insoluble and lighter than water (water, air, and possible land pollution): for a leak, Q = 3000 gm/s; or instantaneous discharge, A = gal on spilled x 3.8 x density x percentage of spillage x 10^3 = gm.

If in the ground-level Gaussian dispersion equation X equals ETLV, then a relationship can be established between the relative concentration ($X\mu/Q$) and downwind distance for an airborne containment under various stability categories. The reciprocal relative concentration ($Q/X\mu$) is used to develop a positive relation with downwind distance, and the equation becomes:

$$K = Q/\pi\sigma_y\sigma_z\ \mu\ (\mathrm{ETLV}). \qquad (31)$$

Since μ is consistent, and σ_y, σ_z is constant for specific downwind distances and specific stability categories, K can be plotted against downwind evacuation distances for selected stability categories (B, D, F). The equation becomes:

$$K = Q \times 10^3/\mu \times \mathrm{ETLV}; \qquad (32)$$

where: Q = source strength (gm/s);
μ = wind speed (m/s); and
ETLV = excursion threshold limit value (mg/m^3).

The reciprocal relative concentration can also be used to plot downwind evacuation distances against crosswind evacuation distances for stability categories unstable (B), neutral (D), and stable (F).

The recommended upwind evacuation distance is selected arbitrarily as one-half the crosswind distance and serves as a buffer safety zone in the event of an unexpected change in wind direction.

Using the Hazardous Material Response Guide of the IEPA, to determine evacuation distances, the downwind distance is read from the calculated value of K.[33] This distance is used to read the crosswind evacuation distance. The plume configuration is determined by the respective weather stability plots. Safety factors are not added to the plots, but are built into the ETLV determination.

APPENDIX E. METHODOLOGIES FOR CALCULATING TOXIC CORRIDORS[34]

The U.S. Air Force Air Weather Service's (AWS) generalized form of a diffusion prediction equation for operational use can be expressed as follows:

$$Cp/Q = KX^{a}U^{b}\sigma(\theta)^{c}(\Delta T+k)^{d} \tag{33}$$

where: Cp = peak concentration at a given downwind travel distance (x);
Q = source strength;
U = mean wind speed;
K = empirical constant;
X = downwind travel distance;
σ = standard deviation of the wind direction;
ΔT = difference between the temperatures at two levels above ground;
k,a,b,c,d = parameters of fit (estimating equation coefficients) determined by least squares regression techniques.

Based on the dependent data set and testing on an independent data set, a diffusion equation was chosen that is reliable for vastly different terrains and climatic regimes:

$$Cp/Q = 0.00211\ X^{1.96}\ \sigma(\theta)^{-0.506}(\Delta T+10)^{4.33} \tag{34}$$

where: Cp/Q = normalized peak concentration (s/m^3);
$\sigma(\emptyset)$ = standard deviation for wind direction (degrees of azimuth);
ΔT = temperature difference (i.e., the temperature at 54 ft (16.47 m) - temperature at 6 ft (1.83 m)) (°F).

Wind direction fluctuation statistics, $\sigma(\theta)$, is difficult to compute accurately without a computer; therefore, a simplified equation that uses only X and T was developed:

$$Cp/Q = 0.000175\ X^{1.95}(\Delta T+10)^{4.92} \tag{35}$$

Equation 3 can be converted to yield the distance [X(ft)] at which the concentration will be below a specific value:

$$X = 0.0388\ (Cp/Q)^{-0.513}(\Delta T+10)^{2.53} \quad (36)$$

Usually solutions of equation 27 have been provided in graphical or tabular form for use by field personnel. The number of toxic chemicals that may be accidentally spilled is quite large, and each provides a unique solution of equation 37; therefore, the number of requested tables is correspondingly large.

The generalized equation used to product the tables of toxic corridor lengths is as follows:

$$X(ft) = P[3.28(29.75/GMW)^{0.513}(Cp/Q)^{-0.513}(\Delta T+10)^{2.53} \quad (37)$$

where P is a probability factor used to determine the probability that w specified concentration is not exceeded outside the corridor, and GMW is the gram molecular weight of the toxic chemical.

AWS has presented three methods for calculating the dimensions of a toxic corridor. For each method, the instructions are outlined as a series of steps, and preferred and alternate approaches are given. All require the following:

- An estimate of the source strength of the chemical (lb/m).
- The temperature difference between 54 and 6 ft (16.47 and 1.83 m) above the ground
- The surface wind direction (degrees of azimuth) and speed (knots) measured as close to the spill site as practicable.

Three of the methods require gram molecular weight of the chemical and its exposure limit as additional input. From this information, the toxic corridor length in feet is determined as well as the corridor width in degrees. A toxic corridor worksheet is available for recording all data and calculations, including a sketch of the corridor. The toxic corridor orientation and dimensions are then relayed to the disaster-response team or other appropriate user, where they are plotted on an appropriate map. The forecaster also adds a forecast of the trend in wind direction for the next hour or two so that the response team is aware of any significant changes that may affect the shape and size of the dispersing chemical plume. The forecaster monitors the weather conditions closely until the spill is under control and updates the corridor forecast periodically.

Method 1. Toxic corridor length tables

Method 1 is most likely to be used if there is a toxic corridor length table for the spilled chemical. Such tables are provided for 31 chemicals and are based on solutions to equation 37 for given source strengths and values of the 54- to 6-ft (16.47 to 1.83 m) temperature difference (ΔT). The preferred approach to determine the source strength is to obtain the best estimate possible from the disaster-response force. The following alternate means of estimating source strengths will result in any error being on the high side.

- For small amounts of liquid or gaseous material (< 2,000 lb (908 kg)), the worst case can be assumed to be a total release in one minute.
- For large amounts of gas ($\geq$ 2000 lb (908 kg)), the total release is assumed over a 5-minute period.
- For large amounts of a liquid, a source strength of 2,000 lb/min is assumed.
- For releases where the amount of material is unknown, the downwind distance the wind would carry the material in 1 hour is used. This is considered an interim forecast and should be updated as soon as better information becomes available.

The preferred approach for determining ΔT is to use a 10-minute record from a 54- to 6-ft (16.47 to 1.83 m) ΔT instrument. Such measurements can also be used by using a sling psychrometer at the 54- and 6-ft (16.47 to 1.83 m) levels of a radar tower. Once the source strength has been estimated and ΔT value is known, the appropriate toxic corridor length table can be used to obtain the corridor length in feet.

Next, the mean wind direction and the variability in the wind direction (R), which is an index of the lateral diffusion of a toxic chemical in the atmosphere, are determined. The preferred approach is to use a 10-minute wind direction trace and eliminate the two farthest direction fluctuations on each side of the mean. Variability (R) is the difference in degrees between the third largest fluctuation on each side of the mean direction.

The toxic corridor can be plotted with this information. The corridor centerline is drawn from the spill or release point to the point on the wind direction circle that corresponds to the direction the mean wind is blowing toward (i.e., 180° from the recorded mean direction). One-half of the corridor width (W/2) is plotted on each side of the centerline. Lines drawn from origin through W/2 define each side of the corridors. If the wind speed is 3 knots or less, the toxic corridor is assumed to be a circle that has a radius equal to the corridor length. The toxic corridor is the forecast area, within which the probability is 90 percent that the concentration of a toxic chemical will exceed a specific exposure limit.

Method 2. Chemical and diffusion factors

Method 2 will most likely be used if a toxic corridor length table is not available for the spilled or release chemical. The diffusion equation (equation 37) has been separated into its chemical and diffusion components. The toxic corridor length is defined as the product of the chemical and diffusion factors. Tables are available for chemical and diffusion factors and nomograms for determining chemical and diffusion factors. Once the toxic corridor length is known, the forecaster follows steps identical to those in method 1.

Method 3. Universal nomogram

Method 3 requires more independent data and would be applicable for unusual combinations of toxic chemical and exposure limits. A universal nomogram is provided for determining toxic corridor length. The estimated source strength, observed T, appropriate exposure limit, and gram molecular weight for the spilled or released chemicals are entered into the three-part nomogram, and a corridor length is read from the intersection point of two projected lines. Once the toxic corridor length is known, the forecaster follows steps identical to those in method 1.

The Atmospheric Sciences Laboratory (ASL) of the U.S. Army Electronics Research and Development Command has developed near-real-time computer programs that depict the hazard corridors that would result from the accidental release of toxic chemicals. These programs are known collectively as toxic corridor prediction (TOXCOP) programs.

APPENDIX F. MEASURES USED BY STATE TRANSPORTATION AGENCIES TO MITIGATE CHEMICAL WATER POLLUTANTS RELATED TO HIGHWAY FACILITIES[25]

Responses were received from 49 of the States and the District of Columbia with varying amounts of information. Several States described special treatment measures used at specific locations. Many States indicated studies were being conducted to identify nonpoint source pollutants so they could develop effective treatment measures. A few States indicated no mitigation was being done primarily because no pollutant problems had been identified, or if they did exist, were of low priority as compared to other pollution problems.

A. Pollutants and Measures

Pollutants and measures identified are listed according to the number of responses from the State transportation agencies. A discussion of each category follows:

1. Pavement runoff (chemical constituents)

Eighteen States reported a concern with chemical constituents in pavement runoff water, and many of these were making or have undertaken a study in this area. Identification of roadway pollutants appears to be the main emphasis of these studies. Measures to cope with problems identified in study findings were not mentioned.

2. Detention ponds/sediment basins

Sixteen States discussed variations of detention ponds and sediment basins to hold runoff water. In some cases, the basins were for settling sediment particles. Other uses included infiltration, removal of chemicals, and diversion structures.

3. Hazardous spill programs

Fifteen States mentioned hazardous material spill and abatement programs. Methods generally were directed at containment of the spill, notification of safety authorities, including identification of the material, and cleanup. Safety improvements were identified as a preventative measure.

4. Leachates from mineralized and problem pH soils

Eleven States indicated a concern with leachates in exposed mineral bearing material and acid/alkaline soils. Methods used to eliminate the chemical leachate included covering it with top soil, burying the material within embankment sections, and removing adverse material with disposal at an approved site. If the material had an economic value, such as coal, the contractor was allowed to mine it.

5. Drainage diversion

Ten States described diversion techniques to pass drainage water around sensitive water receptors to maintain the quality of the existing water resources. Two States mentioned projects where the highway alinement was moved to prevent contact with the water.

6. Vegetated waterways

Seven States reported the use of grassed waterways and vegetation barriers to trap and filter pollutants in runoff water. Studies conducted by two States showed this to be an effective method for improving water quality.

7. Detention structures with baffles, skimmers, filters

Six States described the use of detention structures with various baffles, skimmers, traps or filters to remove oil and grease, floatable material, nutrients, and sediment particles resulting from runoff from the traveled way.

8. Sandblasting debris in bridge repainting

Three States discussed concern with lead and other material produced during sandblasting operations to prepare steel bridges for repainting. Shrouding systems consisting of net curtains were used by two States to trap materials. One State had specifications for the use of clean sand as material for sandblasting.

9. Mechanical water treatment plants

Two States reported using mechanical water treatment plants to separate and remove pollutants from pavement runoff and slope drainage. One plant was used to remove aluminum from seeps within the highway right-of-way. The other treatment plant removed oil and grease, floatables, nutrients, and sediment.

10. Leachates from solid waste

Two States discussed leachates from solid waste material disposed within the project. The principles of landfill operations, such as spreading soil lifts over waste layers and compacting, were used to prevent groundwater contamination.

11. Cofferdams and dewatering pollutant controls

Two States mentioned the use of cofferdams around piers and pilings with pollutant control of dewatering operations wherein the water is piped to onshore ponds for settling of solids.

12. Miscellaneous

Other methods mentioned included: monitoring for leaks of fuel storage tanks, specifying the storage and use of chemicals, statewide planning to assist industry in recycling material to minimize potential hazardous cargo spills, training in water quality and pollution control technology, testing of monitoring water, street sweeping to remove particles along roadways, and undertaking comprehensive environmental investigations to identify possible pollutant problems.

B. Conclusion

Most State highway agencies are addressing nonpoint source pollution problems related to water quality. The measures vary with the main emphasis on using detention or sediment basins. Hazardous material spill programs were also mentioned as a major effort to protect the quality of the State's water resources.

There appears to be a significant need to develop and evaluate water pollution control abatement alternatives for a number of potential transportation related pollutants such as oil and grease, toxic metals, nutrients, and solids. These measures could be incorporated into the Best Management Practices for each State under Section 208 of Public Law 92-500, the Federal Water Pollution Control Act Amendments.

C. Implementation

Measures discussed in this study will be evaluated for use within Caltrans by the various functional units and Trans-Lab. Many of the measures, or modifications of them, are already being used. Studies will be undertaken at appropriate times to investigate additional measures that show promise for reducing chemical impacts to wate quality from transportation facilities.

The research study under which this interim report was prepared will continue with the investigation of two specific mitigation measures: 1) use of detention basins to trap chemical pollutants contained in roadway runoff, and 2) evaluation of alternative measures to mitigate leachates from road slopes.

D. Summary of State Transportation Agency Responses

In December 1978, letters were sent to the 50 State highway and transportation agencies and to the District of Columbia requesting information on methods used to mitigate potential water quality impacts related to highways. The letter asked the agencies to specifically identify those measures used to mitigate chemically-related impacts for items such as constituents in pavement runoff, hazardous spills, leachates from exposed minerals or other material in road slopes, and other chemicals associated with the roadway operation. The effects of deicing salts and mitigation measures were not addressed in this study because of other more comprehensive investigations on this subject. Erosion and sediment were not included either because of the extensive amount of work that has been conducted in this area. The reader is referred to reports in the literature for information on deicing salts and erosion control.

APPENDIX G. CHICAGO AREA FREEWAY TRAFFIC MANAGEMENT PROGRAM--ITS MITIGATING EFFECT ON HAZMAT INCIDENTS[35]

The Illinois Department of Transportation (IDOT) operates a model freeway traffic management program in the Chicago area. There are three major parts to the IDOT program: (1) the Traffic Systems Center (TSC); (2) the Communication Center; and (3) the Emergency Traffic Patrol (commonly referred to as "minutemen"). This program helps maintain urban mobility while promoting motorist safety in Chicago-area expressway traffic, which in some sections is now peaking above 300,000 vehicles per day.

The program does not operate specifically to spot or mitigate hazardous materials incidents, but the fact of its existence is a great advantage in this regard. It could be considered a very important "fringe benefit." With up to 40 vehicles patrolling the system, incidents have a high probability of being spotted soon after occurrence. Minor hazmat incidents can be taken care of quickly; major ones can be reported immediately, and initial response actions coordinated by the minutemen often mitigate the consequences.

1. Traffic systems center

TSC plans, develops, designs, implements, operates, maintains, and evaluates such highly complex and specialized urban traffic systems as computerized expressway surveillance, incident management, ramp metering, driver information, and traffic report networks.

The Chicago-area expressway network features the world's first and largest freeway traffic surveillance and control system, which operates from TSC. The real-time system covers 110 miles, with 1,650 detector locations, 91 ramp controls, and one changeable message sign, all centrally supervised. Six commercial radio stations and one commercial traffic reporting service have direct terminal hookups with TSC computer. More than 40 radio and TV stations provide traffic reports based on the computerized information, demonstrating a unique and successful government/media partnership.

a. Expressway surveillance: The TSC central computer system in Oak Park, IL, keeps track of current traffic conditions system-wide and helps spot congestion-causing accidents, disabled vehicles, and other incidents.

b. Ramp control: Ramp metering signals now control entrance ramp traffic at 91 locations along various Chicago-area expressways.

Centrally timed by the TSC computer system in Oak Park, the ramp signals help balance entering traffic demands with available expressway capacities. Signal timings are varied continuously as measured ramp and expressway traffic flows indicate how entering ramp traffic should best be merged into machine expressway traffic.

c. Traffic reports: Several radio stations hook their own teleprinters and terminals onto a network served by the TSC computer. More than 40 Chicago-area radio and TV stations provide traffic reports based on the TSC expressway surveillance information. Such reporting to motorists en route or at home/work helps the driving public avoid major trouble spots by changing routes or by delaying trips.

d. Surveillance computer network: The Communication Center, the Emergency Traffic Patrol, and IDOT's Management and traffic personnel are tied by TSC into an intra-agency computer terminal network for traffic information exchange and dissemination of special messages to the public via keyboards reporting through the TSC media feed. Terminals are also provided to the State police and loaned to public transportation agencies to expand the travel information coordinated through the TSC computerized media reports.

e. Changeable message signing: Since early 1982, TSC has operated its first changeable message sign system at one expressway location in advance of parallel roadways covered by monitoring detectors. The bridge-mounted, 1-line, 32-character, 18-in letter, disc-matrix message sign displays current information advising motorists of downstream traffic conditions. Plans for a network of more changeable message signs have been already made.

f. Surveillance duct network: Since 1978, TSC has been converting leased data lines to its own communications network by installing ducts and cable in the base of median concrete safety barriers with laterals connecting roadside equipment cabinets.

2. Communications center

The Communications Center, staffed around the clock, handles all District radio dispatching and "hot lines," and coordinates all traffic and maintenance information and operations, including communications for the Emergency Traffic Patrol vehicle fleet. Remote computer terminals and map displays connected to the TSC surveillance computer allow the Communications Center to serve as the primary incident detection site during overnight and weekend periods when TSC is not staffed. The Communications Center plays a major role in all incident management situations, acquiring coordination between IDOT resources as well as cooperation with police, fire, and other agencies.

3. Emergency traffic patrol

The Emergency Traffic Patrol minutemen provide mobile surveillance and respond to freeway incidents on 100 centerline miles or 718 lane miles, including ramps, of the Chicago-area expressway system 24 hours a day, seven days a week. The primary objective of the minutemen is to respond to any disruptive incident on the Chicago expressway system and take immediate corrective action to restore the normal traffic flow. Whenever traffic trouble is initially spotted through the TSC surveillance system, the procedure is to request, through the Communication Center radio dispatcher, the closest available patrol truck to investigate the site of the noted traffic flow disruption. Specific duties of the minutemen are:

- Assisting at accident scenes by rendering first aid; calling for police, fire ambulance, or special equipment services; helping extricate trapped or injured persons; supplementing police traffic control; and removing accident vehicles from the roadway.
- Removing accident and nonaccident debris from the roadway or calling for extra clean-up help and special equipment, sanding for oil slicks, salting, and removing or assisting with the removal of dead animals.
- Assisting motorists by towing disabled vehicles and abandoned vehicles from hazardous locations; providing gasoline, tire-changing aid for women or the physically handicapped; and water for overheated radiators; lending tools or assisting with minor repairs; and, if necessary, transporting motorists off the expressway.
- Establishing emergency traffic detours by placing appropriate temporary traffic cones, barricades, flares, signs, and lights, and closing ramps or lanes.
- Assisting at special expressway maintenance or construction work by protecting workmen and assisting in placing traffic controls.

- Reporting traffic information to the Communication Center for distribution to IDOT traffic engineers and the news media.
- Reporting State property damage, including signs, fencing, guardrails, inoperative signals or lighting, pavement defects, and drainage problems.
- Providing travel information by giving directions, road conditions, and map-reading assistance to motorists seeking aid.
- Warning pedestrians to keep off the expressway and notifying enforcement authorities when persons or vehicles do not voluntarily comply with their requests.
- Assisting at disaster scenes with manpower, equipment, and traffic controls.
- Surveillance of lane closures put up by contractors, maintenance, and outside agencies. They check that all contractors have authorization and proper traffic control devices in place. If any unauthorized lane closures are found, minutemen will be directed to remove the closures and direct the work crews to leave the freeway.

The patrol fleet of IDOT includes 35 emergency patrol vehicles, 9 Broncos, 3 heavy duty tows, one crash crave, one tractor-retriever, a sand spreader, and a heavy rescue and extrication truck. In 1984, the patrol fleet logged more than 1.5 million miles on the expressway system, handling 91,584 incidents or assists.

4. Patrol assignments

Twelve patrol assignments operate on overlapping shifts. The patrol routes also overlap to increase coverage of high incident sections, such as a 2-mi (3.22 km) long bridge without shoulders on the Dan Ryan Expressway. Foremen patrol the entire system in light utility trucks and provide supervision, guidance, and assistance to the minutemen.

5. Training

To handle the various duties and hazards common to urban freeway operations, personnel receive special training in patrol procedures and operational techniques. Periodic classes provide training in advance first aid, CPR, firefighting, basic auto extrication, city police coordination, radio communications, lane closures, traffic control, heavy equipment use, and emergency recovery procedures.

6. Results

Evaluation of the operational experience with the large-scale expressway surveillance and control system in the Chicago area determined that electronic traffic aids can be used on existing highway systems to increase the efficiency and safety of traffic flow. Reductions in peak-period congestion (up to 60 percent) and accidents (up to 18 percent) resulted from expressway surveillance and control techniques, which are only a small part of the overall program.

The overall freeway traffic management program capital investment, plus annual operating and maintenance costs, are returned in road user benefits in excess of normal range for highway improvement projects. Traffic using the network under traffic management generates more than $40 million in motor fuel taxes each year. The funding for surveillance, communications, control, service patrols, and other traffic management services represents a direct return to the public using heavily traveled roadways.

The Chicago area case study demonstrates successful progress toward reducing congestion, improving flows, increasing safety, conserving energy, expediting emergency responses, and providing motorist aid and information. Further progress can be expected as operational experience and equipment development introduces refinements and implementation of additional electronic traffic aids helpful to the overall program.

REFERENCES

1. Barber, E. J. and L. K. Hildebrand, "Guidelines for Applying Criteria to Designate Routes for Transporting Hazardous Materials," Federal Highway Administration FHWA-IP-80-15, Washington, D.C., November 1980.

2. Harwood, D. W. and E. R. Russell, "Present Practices of Highway Transportaion of Hazardous Materials," Final Report, Federal Highway Administration FHWA-RD-89-013, June 23, 1989.

3. Russell, Eugene R., "Protective Systems for Spills of Hazardous Materials," Volume I: Final Report, Federal Highway Administration FHWA-RD-89-173, September 1989.

4. Keffer, Bill, Chief, Hazardous Materials Response Section, Environmental Protection Agency, Region VII, Private conversation, June 1987.

5. United States Department of Transportation, Emergency Response Guidebook, DOT P5800.4, Washington, D.C., 1987.

6. Viner, John, Federal Highway Administration, Fairbank Turner Research Facility, Private conversation, September 1987.

7. "Special Investigative Report--Survival in Hazardous Materials Transporation;" National Transportation Safety Board, Bureau of Technology, NTSB-HZM-70-4, December 6, 1979.

8. Hirsch, T. J., W. L. Fairbanks, and C. E. Buth, "Concrete Safety Shape with Metal on Top to Redirect 80,000-lb. Trucks," Research Report 416-1, Texas Transportation Institute, Texas A&M University, College Station Dec. 1984.

9. Hirsch, T. J., "Bridge Rail to Restrain and Redirect Buses," Research Report 230-3, Texas Transportation Institute, Texas A&M University, College Station, February 1981.

10. Hirsch, T. J. and A. Arnold, "Bridge Rail to Restrain and Redirect 80,000 lb. Trucks," Research Project 230-4F, Texas Transportation Institute, Texas A&M University, College Station, November 1981.

11. Hirsch, T. J. and William L. Fairbanks, "Bridge Rail to Restrain and Redirect 80,000 lb Tank Trucks," Research Report 911-1F, Texas Transportation Institute, Texas A&M University, College Station, February 1984.

12. Hirsch, T. J., "Analytical Evaluation of Texas Bridge Rails to Contain Buses and Trucks," Research Report 230-2, Texas Transportation Institute, Texas A&M University, College Station, August 1978.

13. Noel, J. S., C. E. Buth, and T. J. Hirsch, "Loads on Bridge Railings," Transportation Research Record, 796, Washington, D.C., 1981.

14. Kimball, C. E., M. E. Bronstad, J. D. Michie, J. A. Wentworth, and J. C. Viner, "Development of a Collapsing Ring Bridge Rail System," Federal Highway FHWA-RD-76-39, Washington, D. C., January 1976.

15. Perrone, N., "Thick-Walled Rings for Energy-Absorbing Bridge Rail System," Report No. FHWA-RD-73-49, Washington, DC, December 1972.

16. Ervin, R. D., C. C. MacAdam, and M. Barnes, Influence of the Geometric Design of Highway Ramps on the Stability and Control of Heavy-Duty Trucks. Transportation Research Record 1052, Washington, D.C., 1986, pp. 77-89.

17. A Policy on Geometric Design of Highways and Streets, USA. American Association of Highway and Transportation Officials, Washington, D.C., 1984.

18. Cirillo, J., S. Dietz, and R. Beatry. Analysis and Modeling of Relationships Between Accidents and the Geometric and Traffic Characteristics of the Interstate System. BPR Research and Development Report. U.S. Department of Transportation, Washington, D.C., August 1969.

19. MacAdam, C. C., et al., A Computerized Model for Simulating the Braking and Steering Dynamics of Trucks, Tractor-Semitrailers, Doubles and Triples Combinations -- Users' Manual, Phase 4. Final Report UM-HSRI-80-58-Transportation Research Institute, University of Michigan, Ann Arbor, Sept. 1, 1980.

20. Horne, W. B., "Predicting the Minimum Dynamic Hydroplaning Speed for Aircraft, Bus, Truck, and Automobile Tires Rolling on Flooded Parameters." Presented to ASTM Committee E-17 at College Station, Texas, June 5, 1984.

21. Ivey, D. L., et al. "Tractor-Semitrailer Accidents in Wet Weather." The Texas Transportation Institute, Texas A&M University, College Station, May 1985.

22. "Untersuchung uber Linienfuhrung, Bau und Unterhaltun von StraBen in Wasserschultz-und Wassergewinnungsgebieten," Forschung StraBenbau and StraBenverkehrstechnik, 1987.

23. Wilber Smith and Associates "Risk Analysis of Hazardous Material Spills into Scituate Reservoir," Technical Memorandum No. 7, unpublished report prepared for Rhode Island Department of Transportation, May 1985.

24. Wilber Smith and Associates, "A Macroscale Analysis of Drainage Alternatives," Technical Memorandum No. 3, unpublished report for Rhode Island Department of Transportation, December 1983.

25. California Department of Transportation, "A Survey of Measures Used by State Transportation Agencies to Mitigate Chemical Water Pollutants Related to Highway Facilities," Federal Highway Administration, FHWA/CA/80/01, Washington, D.C., January 1980.

26. "An Example of an Environmental Protective System on Bridges Over Watersays: Improvements to Old Mill Road, from Hamlin Road to Old Oxford Road, Durham County, North Carolina," North Carolina Department of Transportation, Raleigh, NC, December 1986.

27. Mustafa, Mohammed, North Carolina DOT, Raleigh, N.C., private conversation, August 1988.

28. "Prevention and Control of Highway Tunnel Fires," Federal Highway Administration, FHWA-RD-83-032, May 1984.

29. Debbert, Walter W., "Aerometric Instrumentation for Real Time Monitoring at Hazardous Spill Sites: Overview of Needs and Resources," Transportation Research Record 902, Transportation Research Board, Washington, D.C., 1983.

30. Hawley, James G., "Remote Sensing and Special In-site Techniques for Detection of Toxic Substances," Atmospheric Dispersion of Hazardous/Toxic Materials from Traffic Accidents, 1984.

31. Shaver, Deborah K. and Robert L. Berkowitz, "Guidelines Manual for Post Accident Procedures for Chemicals and Propellants," U.S. Federal Railroad Administration, Office of Research and Development, Report F04611-80-C-0046, Washington, D.C., January 1983.

32. "Dangerous Goods Truck Route Screening Method for Canadian Municipalities," Consultants Report, Transport Dangerous Goods Directorate, Transport Canada, Vancouver, B.C., January 1987.

33. Kelty, James, "Calculation of Evacuation Distances During Toxic Air Pollution Incidents," Transportation Research Record 902, Transportation Research Board, Washington, D.C., 1983.

34. Kahler, J. P. and J. L. Kiche, "US Air Force Air Weather Service Methodologies for Calculating Toxic Corridors," Transportation Research Record 902, Transportation Reseach Board, Washington, D.C., 1983.

35. Marrs, John T., et al., "Toxic Corridor Predictions Programs," Transportation Research Record 902, Transportation Research Board, Washington, D.C., 1983.

36. Smith, Ted, Manager, Chicago Area Freeway Traffic Management Program, Interview, Chicago, August 1987.