DEVELOPMENT OF MITIGATION MEASURES FOR SAFE TRANSPORTATION OF HAZARDOUS MATERIALS

by

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(ABSTRACT)

The number of hazardous materials transported by truck mode and also the quantities shipped continues to grow every year. In recognition to the potential disasters associated with the occurrence of release of hazardous materials, several studies have been conducted on various aspects of the problem - assessment of risk, container safety, emergency response, disaster assistance, regulations, routing etc. Development of mitigation measures is a relatively new area in hazardous materials research in the sense that it has not been studied comprehensively.

The objective of this study is to determine the appropriateness and effectiveness of different steps to be taken to reduce either the likelihood of hazardous materials accidents/incidents or the damage which would ensue from a release for different hazardous materials. This work attempts to identify, or flag, potentially high risk locations due to spills of hazardous materials, and to evaluate the alternatives to be designed and implemented in order to reduce risk. Appropriate type of roadway improvements for the safe transportation of hazardous material trucks and protective systems that might be incorporated into new or reconstructed highway segments in order to mitigate consequences, are presented for various generalized scenarios. The output of mitigation is the reduced risk value.

This work forms a part of a comprehensive decision making framework integrating the risk identification, calculation and mitigation that can apply to both urban and rural areas.

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1.0 INTRODUCTION

Among the new materials being produced to satisfy the needs of modern life are many that have dangerous properties. These are stored, transported by various modes and used in manufacturing plants. It is inevitable that when these hazardous materials are produced, stored or shipped, there will be spills. These spills, commonly referred to as incidents, are usually capable of causing damage to people, property and environment and invariably receive widespread attention.

In recognition of the potential disasters associated with the occurrence of release of hazardous materials, a number of studies are being conducted at the state and federal level on various aspects of hazardous materials problem - assessment of regulations, risk, container safety, emergency response, clean-up, disaster assistance, vehicle inspection, routing, data collection, and highway design. Two primary questions are usually raised by the authorities in the transportation of hazardous materials;

- What is the level of risk ?
- What mitigation measures will reduce the identified risk ? [13].

The Pennsylvania Department of Transportation through its research project "Hazardous Materials Movement", wants to develop a decision-making framework that can address these questions for the movement of hazardous materials on its highways.

The Commonwealth of Pennsylvania as shown in Table 1.1, accounted for the highest number of hazardous material incidents in the nation between 1971 and 1983 with 90 % of incidents being highway related. Also, the state ranks 6th as either the origin state or the destination state of hazardous material shipments involved in incidents nationwide in 1983. There are over 6000 companies and businesses in Pennsylvania who deal or produce hazardous materials, ranging from small dry-cleaning companies to major firms such as U.S. Steel. Anywhere from one or two drums to thousands of tons of hazardous substances may be produced or used by any Pennsylvania firm during the year. This indicates that the movement of hazardous materials in the Commonwealth of Pennsylvania is sizable and needs to be addressed to avoid potential catastrophic events [13].

1.1 Objectives

The objective of this project is to develop a comprehensive decision making framework integrating risk identification, analysis and mitigation measures that will apply to both rural and urban areas. The project was divided into nine tasks which were to be performed in order to accomplish the overall objective.

Task 1: Event Definition - This concerns the definition of suitable, aggregate classes of hazardous materials to be studied as well as establishing quantifiable values for the behavior of each class.

Task 2 : Macro-analysis (Statewide comparative analysis) - Developing a modeling scheme which can evaluate the relative magnitude of risk and vulnerability for each jurisdiction in the state in order to identify areas deserving more detailed study.

Table 1.1

DISTRIBUTION OF HAZARDOUS MATERIAL INCIDENTS IN VARIOUS STATES
(Top 10 States)

State	Total Incidents	% Highway Related	% Rail Related
Pennsylvania	13,459	90	3
Ohio	9,439	95	4
Illinois	7,142	85	14
Texas	6,885	78	20
California	6,147	77	20
New York	5,979	94	4
Tennessee	5,635	85	4
North Carolina	5,318	94	6
Georgia	5,257	91	8
Michigan	4,917	94	6

Source: U.S. Department of Transportation, Materials Transportation Bureau.

Task 3 : Data Source Identification - This refers to locating potential sources of information for detailed risk modeling at the local level as well as the collection of field data when necessary.

Task 4 : Micro-analysis (Local Analysis) - Developing a modeling scheme which can evaluate the magnitude of risk for a local highway network (e.g., a county's network). Such an analysis should be able to find minimum risk paths in the network and consider those routes which have not been associated with hazmat releases.

Task 5 : Mitigation Measures - Involves studying of the effectiveness and appropriateness of different steps to be taken to reduce either the likelihood of incidents or the damage which would ensue from a release for different hazardous materials. The results of this study would aid in determining the most effective strategy to be implemented for previously modeled situations.

Task 6 : Area Identification - Testing, validation, and refinement of the model achieved from Micro analysis and Mitigation measures on five specific sites identified by the department.

Task 7 : Detailed Analysis - Site specific information for five selected areas will be collected to meet the needs of the Risk Assessment model for calculating and analyzing the risk levels.

Task 8 : Action Recommendation - Recommended mitigation measures will be provided for reducing the risks determined in the detailed analysis, Task 7.

Task 9 : Model Refinement / Final Reports - The model structure and the mitigation measures might be revised or redefined based on Pennsylvania DOT (Penn DOT) recommendations and public comments where requested.

1.2 Scope of this Research

This research covers task 5 - Mitigation Measures. This involves development of protective systems in order to reduce risk due to the movement of hazardous materials. The risk is made up of two parts - probability of occurrence and consequence of an incidence. The objective is to reduce either the probability of an incident occurring, or the consequences after an incident has occurred, or both. This objective can be met by either physical systems such as barrier rail or regulatory measures such as routing restrictions that can:

- Reduce the probability of an accident occurring,
- Reduce the probability of release given an accident (incident), or
- Reduce the severity of the consequence.

In addition to these there are a wide spectrum of emergency response measures which can be considered. However, these are not within the scope of this research because, this task was intended to develop measures which are a direct responsibility of the department of transportation or highway department and can provide long term protection when constructed and/or implemented.

This narrow focus of this project has posed problems of little or no available literature. There are very few protective systems available now which corresponds to our needs, and no measure of effectiveness are available. Hence an expert system approach has been adopted in order to obtain ideas about protective systems and estimate of their effectiveness. In order to reduce accident probability, there is literature on highway elements and their relationship to accidents. However, there is no literature on the effectiveness of improved highway elements in terms of truck accident reduction.

1.3 Organization of the Work

Chapter two deals with various improvements that can be can considered in general as obtained through a literature review. This includes geometric design considerations for trucks, available protective systems and their effectiveness.

Chapter three presents an analysis of databases conducted as a part of the whole project. This is helpful in the development of a risk model and mitigation measures. This also provides the reader with an insight into characteristics of hazardous material accidents/incidents in Pennsylvania.

Chapter four presents an overview of the proposed risk model. The model is used to determine risks associated with hazardous materials transportation on a highway segment or route.

Chapter five deals with various mitigation measures. This includes the approach towards development of protective measures, methodology used in their selection, and their effectiveness, as well as the effectiveness of ordinary improvements to highway geometry and maintenance. Chapter six shows the results of the model when applied to some sites in Pennsylvania.

Conclusions and possible extension of the work are presented in Chapter seven.

2.0 LITERATURE REVIEW

The objective of this task was to find protective systems that reduce the likelihood of an incident and the ensuing consequences and to determine the effectiveness of such improvements. A major criteria was that the recommended improvements be of protective system type and not emergency response measures. The difference among the two being that emergency measures will be initiated after the accident has taken place whereas protective system type measures are already in place in the highway system and play an important role in reducing the risk. In order to accomplish the above objectives, literature review has been concentrated in the following areas:

- Effect of current geometric design standards on truck safety
- Effectiveness of geometric design improvements on truck accidents
- Protective systems available to reduce accidents or accident severity and to mitigate the consequences due to hazardous material incident.

Though the study involves safety of hazardous materials transportation, this literature considers movement of trucks in general, since there is no literature specific to movement of hazmat carrying trucks within the context of the study, and also because most of the hazardous materials considered in this study are carried by trucks that have same accident probability and characteristics as all trucks.

2.1 Geometric Design Considerations for Trucks

Parallel to recent improvements in the highway system, and vehicle technology, the trend has been toward ever larger trucks and toward growth in the volume of freight, moved by trucks including hazardous materials. Though increases in vehicle size have yielded substantial improvements in transport productivity, they have always raised concern about safety. This is because the highway system is a fixed entity and incorporating changes in it due to changes in the vehicle fleet that exceed past design criteria or policy would be a very expensive venture. Hence many states have established regulations limiting truck travel on their highways. However, the Surface Transportation Assistance Act (STAA) of 1982, has authorized the U.S. Secretary of Transportation to designate a national network of interstate and other major highways on which trucks approved by the act (STAA vehicles) could travel without restriction. The act also required states to provide "reasonable access" from this network to terminals and to also provide facilities for food, fuel, repairs and rest (service facilities) [30]. This act has brought forward the issue of the adequacy of safety of current geometric design standards and a number of studies have been carried out.

The primary guide or policy on highway geometric design is the American Association of State Highway and Transportation Officials (AASHTO) "A policy on Geometric Design of Highways and Streets; 1984", better known as the green book. The minimum geometric requirements and design policies for safe movement of vehicles are listed in the book. However, the major emphasis has been on the automobile as it accounts for a majority of travel. Also, the current technical data were essentially completed before the enactment of the act (STAA of 1982), which

increased the allowable maximum dimensions for truck, tractor-trailer combinations [27]. Thus, these larger trucks were not given as much consideration as they probably should have when determining the design considerations.

The physical characteristics of a vehicle and the proportions of variously sized vehicles using the highways are positive controls on geometric design. The following elements were identified as those that may be affected by a change in vehicle dimension and weight, based on the current principles and practices [8, 27, 30]:

- Lane and Shoulder width and type
- Stopping sight distance
- Passing sight distance
- Horizontal curves
- Vertical grades
- Intersections
- Roadsides and sideslopes.

2.1.1 Lane Width

The following observations were made on the lane width in many studies:

1. Only on 24-ft pavements were drivers apparently satisfied with both edge and body clearance.
2. Drivers of passenger cars prefer a body clearance of about 5 ft when meeting other vehicles. This cannot be attained on pavements that are less than 22-ft wide [27].

AASHTO recommends a lane width of 11-13 ft. However, for safe and tension-free operation of 102-in wide trucks, lane width of 12 ft has to be provided. On lanes with

that of less than 12 ft width it may be necessary to control the number and movement of trucks [1].

2.1.2 Shoulders

Shoulders are mainly provided to accommodate stopped vehicles, for emergency use including emergency response to incidents, and for lateral support of the pavement base and surface courses. AASHTO recommends that, for heavily traveled and high-speed highways, the usable shoulder width should be at least 10 ft but preferably 12 ft [1]. It has been found in past studies that as right-shoulder width increases on curves, the accident rate decreases and paved shoulders produce fewer accidents than unpaved shoulders.

Hence for safe operation of trucks, it is considered necessary to have a paved shoulder with width of at least 10 ft.

2.1.3 Stopping Sight Distance

Design stopping distance is the minimum distance required for a vehicle traveling near the design speed to stop before reaching an object in its path [1].

$$SSD = 1.47 \times V \times 2.5 + \frac{V \times V}{30 \times (f + g)} \qquad (2.1)$$

where:

SSD = stopping sight distance

V = vehicle speed (miles/h)

2.5 = value assumed to represent perception and reaction times (s)

f = coefficient of friction between the tires and the roadway surface, and

g = percentage grade divided by 100

The first part of the formula gives distance travelled during the driver's perception reaction time. The second part gives distance required to stop after brake application.

The above formula and measuring criterion for minimum stopping distance were derived for passenger car operations, AASHTO states that, although trucks require larger stopping distance from a given speed, the additional braking distance is balanced by the higher eye of the truck operator. Hence there is no change in stopping sight distance requirement for trucks.

2.1.4 Passing Sight Distance

Passing sight distance is the sight distance required to safely complete overtaking of a slower-moving vehicle on a two-lane highway with an operator eye height of 3.50 ft and an object height of 4.25 ft [1].

$$PSD = d(1) + d(2) + d(3) + d(4) \qquad (2.2)$$

where:

PSD = passing sight distance

d(1) = initial maneuver distance (ft)

= 1.47 x t (V - m + a x t/2), where

t = initial maneuver time (s)

V = average speed of passing vehicle (miles/h)

m = speed differential between the two vehicles (miles/h)

a = average acceleration (miles/h/s)

d(2) = distance traveled in the left lane by the passing vehicle (ft) = (Lf + Ls + 150)V/Vi

where:

Lf = Length of faster vehicle (ft)

Ls = Length of slower vehicle (ft)

V = speed of faster vehicle (miles/h)

Vi = speed difference between the vehicles (miles/h), and

150 = additional distance between the two vehicles before and after the passing maneuver (ft)

d(3) = distance at the end of the passing maneuver between the passing vehicle and an opposing vehicle

d(4) = distance traversed by an opposing vehicle

Whereas an increase in vehicle weight and width will have no effect on the elements defined above, an increase in vehicle length will have a pronounced effect on d(2) and d(4).

Since, it is common practice for cars to overtake trucks, additional length will be needed or more abortive passing maneuvers will result when truck length is increased. According to present design standards, the passing sight distance is based on a passenger car passing a passenger car. These should be changed by considering the scenario of a passenger car passing a large truck. Pavement markings that prohibit passing maneuvers should be provided in areas where a successful passing cannot be accomplished. The minimum passing sight distance

requirements considering trucks has been calculated in a study done by Gericke et al. [8] and the values are shown in Table 2.1.

2.1.5 Horizontal Curves

Pavements on curves have to widened sometimes to make operating conditions on curves comparable to those on tangents (AASHTO). This is justified based on truck operating characteristics:

- that the rear wheels track inside of the front wheels (off-tracking).
- the difficulty of steering the vehicle. [1]

The extra width of pavement required is necessary because of the probability of rollover if the vehicle moves onto the shoulder. This is a very serious problem in trucks carrying hazardous material as is evident from an analysis of accidents presented in the next section.

2.1.6 Vertical Grades

According to AASHTO, climbing lanes should be provided on the upgrade side of a two-lane rural highway when:

1. The length of upgrade causes a speed reduction of 10 miles/h or more or
2. The added cost is justified by the volume of traffic and the percentage of trucks.

The size, power, gradeability, and entrance speed of trucks contribute to the performance of trucks on a grade. AASHTO uses a nationally representative truck with a ratio of Gross Vehicle Weight (GVW) in pounds to net horsepower of 300:1 to

Table 2.1

MINIMUM PASSING SIGHT DISTANCE FOR TWO LANE HIGHWAYS
FOR INCREASE IN VEHICLE LENGTH

Design Speed (mi/hr)	Assumed Speed (mi/hr) Passed Vehicle	Passing Vehicle	Avg a (mi/hr)	t (s)	Passing Sight Distance (ft) Calculated L = 65 ft	L = 105 ft	AASHTO	MUTCD
30	26	36	1.40	3.6	1700	1900	1100	500
40	34	44	1.41	3.8	2100	2400	1500	600
50	41	51	1.45	4.1	2500	2800	1800	800
60	47	57	1.48	4.4	2800	3200	2100	1000
65	50	60	1.50	4.5	3000	3400	2300	-
70	54	64	1.50	4.5	3200	3600	2500	1200
75	56	66	1.50	4.5	3300	3700	2600	-
80	59	69	1.50	4.5	3400	3900	2700	-

Source: Gericke et al. [8]

evaluate the performance (acceleration and deceleration) of trucks on grade. This is reasonable due to the current availability of engines to provide 300:1 ratio. [1]

2.1.7 Intersections

A substantial share of accidents occur at intersections - 55 percent of urban accidents and 32 percent of rural accidents [30]. The longer-wheelbase tractor-semitrailers have greater difficulty in negotiating many intersection turns than do passenger cars or shorter-wheelbase tractor-semitrailers because of offtracking problems. However, the number of accidents caused by offtracking is unknown, and predicting whether intersection improvements will reduce accidents is difficult because so many factors, such as sight distance, number of lanes, lane width, traffic volume, and traffic signalization, affect the safety of turns at intersections [30].

AASHTO considers three general cases of required sight distance at intersections, and the designer must ensure that for different assumptions there will be an unobstructed view of both roads. The three cases are:

1. Enabling the vehicles to adjust speed, in which case only reaction plus perception time and one additional second for acute braking is considered;
2. Enabling vehicles to stop, in which case safe stopping sight distance plays a role; and
3. Enabling the stopped vehicle to cross a major highway, in which case the formula used to obtain the required sight distance is

$$d = 1.47 \times V \times [J + T_a] \tag{2.3}$$

where:

d = minimum sight distance along the major highway (ft)

V = design speed

J = sum of perception time and the time required to shift to first gear or actuate an automatic shift

Ta = Time required to accelerate and traverse the distance S required to clear the major roadways

S = D + W + L

D = distance from the near edge of the pavement to the front of the stopped vehicle

W = width of pavement along the path of the crossing veh

L = overall vehicle length

From the above, it can be seen that only case 3 will be influenced by vehicle length and acceleration capability. If the acceleration capabilities of trucks are assumed to be at least the same as that of the critical vehicle, the sight distance has to be adjusted for increased vehicle length.

2.1.8 Roadsides and Sideslopes

It has been found through the analysis of databases that combination vehicles are more likely to be involved in single-vehicle accidents than are passenger cars and that most of the releases of hazardous materials have been caused by single-vehicle accidents. Thus, adequate recovery areas at the road edge that are smooth, flat or without steep sideslopes, and clear of fixed objects, are important to truck safety.

Correcting pavement edge drops, that is, vertical discontinuities at the edge of the paved surface, may also have important safety ramifications [30].

2.2 *Truck Accident Studies*

The primary objective of this literature review was to determine if and to what extent the magnitude of urban freeway truck accidents had been established by prior reports. Specifically, literature search was conducted:

- To determine if the magnitude of large truck accidents on urban highways had previously been quantified and
- To identify problems, biases and reliability of previous large truck studies.

Few research efforts were identified which concentrated on urban freeway truck accidents. Also, the review revealed that the conclusions of truck accident studies are often based on misleading or inappropriate analysis strategies. For example, accidents were frequently categorized by only one type of vehicle involved in the accident. If the accident involved a passenger car and a truck, it is categorized as a truck accident. Subsequent analysis will typically treat it as a truck accident using only truck exposure factors to normalize the data. Thus it does not account for all the elements involved in the accident [9].

Implicit in the use of exposure factors in accident analysis is the premise that, the greater the amount of travel on a given facility, the greater is the amount of risk or exposure to accidents to which vehicles on the facility are subjected. The proper use of rates must reflect the varying amounts of travel, or exposure to risk of each element involved in the accident [9].

Another problem which hinders the analysis of truck accidents is the data. The data are, or are anticipated to be, used to develop statistics that are analyzed for present trends, to identify problems, develop relationships, and perform evaluations. In any evaluation of highway safety using accident rates as a measure, there are two types of data. The first is the accident data. Depending on the issue, various data on accidents may be required. This may range from a simple count of accidents involving a certain vehicle type to a specific aspect of the accident (e.g., when it occurred, type of accident, actions before the accident, driver condition) [19].

Accident measures are typically expressed as accident rates (i.e., accidents per mile of highway or more commonly accidents per million vehicle miles traveled). The denominator that provides the rate calculation is typically called the exposure value. Thus, the second principal type of data is the exposure of vehicles.

Exposure data are important because they are crucial in calculating the likelihood of an accident. To be meaningful, the exposure data must be related to the variable (issue) being evaluated. For example, if an accident rate on a particular route or section for double trailer trucks with a van trailer configuration is being sought, then the volume of these trucks over that route or section is needed as well as the number of accidents. If accident rates are "borrowed" or transferred from other data, its reliability or applicability must be carefully examined [11].

In order to obtain relationships between the truck accidents and other characteristics such as type of highway, geometric features etc., a large statistically valid sample is usually necessary. Accident files such as the National Highway Traffic Safety Administration's (NHTSA's) Fatal Accident Reporting System (FARS) and the BMCS accident files are commonly referred to because they are "the best files we have". They may be biased or limited in scope because of the lack of investigative experience and may not provide important information necessary for analyzing

complex interrelationships to determine design criteria. In addition, there are usually limited measures of exposure by vehicle type and load configuration that can be correlated with accidents by type of truck and load configuration [15].

In summary, none of the many databases and methodologies used in prior studies is sufficiently comprehensive to yield the information required to assess the magnitude of large truck accidents on urban freeways. Studies by Midwest Research Institute (MRI) and Kansas State University (KSU) researched the problem of best accident rate to use and on all recommendations on when to use average and when to use more specific route and/or section data [11].

2.2.1 Roadway Characteristics and Accident Experience

A significant number of studies have addressed the relationship between specific highway design features (as opposed to road class) and motor vehicle accidents. Two limitations of the studies should be kept in mind. First, most of the safety relationships are applicable to two lane rural roads because majority of research focused on rural highways; thus urban highway design features are not specifically addressed. Second, the studies are primarily concerned with passenger cars. Here a few relationships between highway design elements and accidents are summarized [29].

Approximately 60 percent of rural highway fatalities that are caused by single-vehicle, head-on, and sideswipe accidents are affected by lane and shoulder conditions. The research findings indicate that increasing lane and shoulder width can reduce the risk of certain type of accidents. However, pavement widening, per foot of added width, has greater accident risk reduction payoff than does shoulder

widening, and stabilized shoulders reduce more accidents than unstabilized shoulders. For example, widening lanes from 9 to 12 ft without any shoulder improvements is projected to reduce accidents by as much as 32 percent for all types of vehicles. Adding 3 ft of unstabilized shoulder where there was none is projected to reduce accidents by 19 percent, and adding 3 ft of stabilized shoulder increases the projected reduction to 22 percent [29, 36].

Increasing the width of the bridge relative to the width of approach lanes can reduce accidents by an estimated 40 percent. However, a large share of safety gains, nearly one-third, is captured in the first foot of widening [17].

The relationship between accidents and degree of curve must be regarded as rough in nature because horizontal curves are considered in isolation - without regard to the alignment of adjacent highway segments - and because the relationship does not fully correct for interrelated effects of other geometric features. It has been found that, because of the high rate of single-vehicle accidents on highway curves, low-cost roadside safety improvements on highway curves may be one of the most effective Resurfacing, Restoration and Rehabilitation (RRR) safety improvements. The accident rate reduction is particularly true for improvement of low-height fill slopes and removal of trees to improve the clear-zone width on the outside of curves carrying more than 2,000 vehicles per day [29].

There are a number of studies on the relationship between geometric elements and accident frequencies. In NCHRP project 3-25 [17], literature reviews of over 400 reports and publications are presented. However, as mentioned all of them consider motor vehicle travel in general, and are not specific to movement of trucks. It was decided that these be used at present in the model as default values and can be replaced later by truck accident reduction factors when available.

2.2.2 Protective Systems to Mitigate Spill Consequences

The concept of designing protective systems into highway systems specifically to prevent or mitigate hazardous material spills is a new and unique concept. No published literature exists that directly addresses this concept. Russell at Kansas State University conducted a study for FHWA but the final report has not been published [24]. In this section, literature on systems that could be adapted to the concept, such as drainage containment systems, high-strength barrier rail, etc. are presented.

2.2.2.1 Maintenance of Water Catchment Areas

A part of this literature is based on a German report on protecting potable water supplies [32]. It is important because it specifically addresses mitigation of hazardous material (hazmat) runoff into potable water supply areas and sensitive environmental areas. German law requires that highway alignment 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, 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 flow.

In highways in low lying areas, the permissible thickness of natural soil left above groundwater depends upon the geological formulation and on the hydrological

conditions of the subsoil. The roadbed has to have a sufficiently thick upper layer of soil cover above the groundwater such that spilled hazmat will not reach the groundwater. Studies of specific materials and soil types should be made. In case sufficient upper layer or soil cover does not exist, the subsoil has to be sealed by constructing a watertight protection layer made of impervious material.

2.2.2.2 High Performance Bridge Rail Systems

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 [24].

The gravity of the problem was evident, when a tank truck carrying ammonia went through an upper deck bridge rail on a Houston freeway overpass and overturned and ruptured on the freeway below in 1976. Six people were killed, 78 hospitalized and more than 100 were injured. Research on bridge rail to restrain and redirect large trucks has been carried out with encouraging results [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 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 van type tractor/trailer combination impacting at 15 degrees and 50 mi/h [12].

2.2.2.3 *Other Protective Systems*

Another area of protective system development is detection and communication equipment. To facilitate quick reporting of an accident by the motorists present, installation of emergency phones has been recommended. A quick response often mitigates greater damage. Rapid transmissions of alarms from fire scene to proper authorities enhances their effectiveness. Fire alarm pull boxes should be located beside each telephone. Further research is being carried out in order to develop spill sensors which can be used to monitor locations where incidents would cause catastrophic consequences. The current state of the art of ambient chemical instrumentation and meteorological 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 [6, 17, 21, 22].

In addition to the above, a number of regulatory measures are in effect in special areas of catastrophic potential such as tunnels. Flammable and combustible liquids are not permitted in tunnels and there are restrictions on the amount of material carried. Other regulatory measures include restricting the hours of transportation, bypassing high density areas, environmentally sensitive areas etc.

The effectiveness of the above mentioned protective systems is not available at present because of insufficient history. There is a need for research in this area.

3.0 ANALYSIS OF DATABASES

Three databases of hazmat accidents, truck accidents in general and accidents involving hazmat carrying vehicles in particular were analyzed in order to review the reasons for truck accidents and container failures on highways leading to the release of hazardous materials, type of material released and their potential to cause harmful events in the state of Pennsylvania. The databases are Research and Special Programs Administration's "Hazardous Material Incident Reports" (HMIR), Bureau of Motor Carrier Safety (BMCS) truck accident database, and Pennsylvania Department of Transportation Traffic Accident data.

RSPA Hazardous Materials Incident Reports is the data source at national level which focuses on various incidents resulting in release of hazardous materials. BMCS truck accident database is also at national level, which, in addition to details of an accident, also has data as to whether or not a hazmat carrying vehicle was involved in the accident and whether or not a release had occurred due to the accident. Pennsylvania DOT Traffic Accident data has information about all traffic accidents occurring in the state of Pennsylvania and also data as to whether or not a hazmat substance was involved. However, there is no mention as to whether a hazmat release has occurred.

The following are the reporting requirements of the two federal databases selected for analysis.

RSPA HMIR Data: Any incident that occurs during the course of transportation (including loading, unloading, and temporary storage), which results in an unintentional release of hazardous material from a package or tank shall be reported in writing within 15 days of the date of discovery of the incident [3].

Moreover, if any of the following occurs, as a result of hazardous material release, that incident shall be reported immediately.

- A person is killed
- A person receives injuries requiring hospitalization
- Estimated carrier or other property damages exceed $ 50000
- Fire, breakage, spillage, or suspected contamination occurs involving shipping of Radioactive Material and/or etiologic agents (viable microorganism or its toxin which may cause human disease)
- A continuing danger to life exists at the scene of the incident.

There is no minimum requirement for reporting the incident. Any incident, however small the spillage might be, will be considered if reported.

The reporting is not mandatory, but voluntary.

BMCS data: This data contains descriptive data of accidents involving motor carriers reported to the Federal Highway Administration. The following types of motor vehicle accidents are termed 'reportable':

- A fatal accident
- An accident with injury to a person, who as a result, received medical treatment away from the scene of accident
- An accident with total damage to property exceeding $ 4400.

The term 'reportable' accident does not include:

- An occurrence involving only boarding and alighting from a stationary motor vehicle
- An occurrence involving only loading or unloading of cargo
- An occurrence in the course of farm-to-market agricultural transportation by motor carrier
- An occurrence in the course of operation of a passenger car by a motor carrier and not transporting hazmat.

The reporting requirements of BMCS especially the minimum damage requirements was changed a couple of times in the past 4 years. Between 1973-1985, the minimum damage requirement was $ 2000. This was changed to $ 4200 from January 1986 and remained so till March 1987. Starting March 1987, the minimum damage requirement was again changed to $ 4400.

Penn. DOT Traffic Accident Data: Pennsylvania Department of Transportation Traffic Accident data is based on police accident records. There is no minimum reporting requirements. All the accidents have to be reported to the police and then will be recorded in the Penn DOT Accident data. However, in this database, there is no information as to whether or not a hazmat release has taken place. The only information relevant to hazmat analysis is whether or not a hazmat was involved in the accident.

3.1 *Analysis of Hazardous Material Incident Report data*

The hazardous material incidents occurred in the state of Pennsylvania obtained from the HMIR data have been analyzed for the years 1983-1987. The HMIR data has reports of all unintentional hazmat releases independent of whether they take place during the highway shipment of the hazmat (on highway) or in other locations (off highway). As our study focuses mainly on incidents occurring on-highway, all the following tables show the distribution of hazmat incidents occurring on-highway. In the following sections, hazmat incidents are distributed based upon their cause, characteristics, result of accidents, amount of spill etc. This stratification would provide a good idea about the results and consequences of hazmat incidents occurring in Pennsylvania.

3.1.1 Causes of Hazmat Incidents

Table 3.1 presents the distribution of hazmat incidents obtained from HMIR data by type of failure. The major failure types are valve or fitting failure (37.9%) and cargo shifting (30.8%) followed by body or tank failure (20.1%). Traffic accidents constitute only 5.5% of all incidents. However, when severe incidents are considered, traffic accidents account for 56.9% of the incidents.

A severe incident is one that involves:

1. a fatality or injury caused by hazmat release, or
2. property damage of $ 10000 or more caused by hazmat release, or
3. a fire or explosion. [11]

In Table 3.2, hazmat incidents are distributed by cause of failure. Most of the hazmat incidents are caused by human error and do not result in severe incidents. Only 1.4% of these incidents are considered severe. Traffic accidents, though responsible for only 5.5% of total incidents, account for about 57% of severe incidents. The other important cause of severe incidents is package failure (25.9%).

3.1.2 Type of Hazardous Material Involved

HMIR data has report of type of hazmat released identified by hazard class and also by the name of chemical. Table 3.3 shows the frequency distribution of release of each class of hazmat for all incidents in general, and traffic accidents in particular. Corrosive materials and flammable liquids are the most common classes of hazmat released considering all incidents, whereas in traffic accidents flammable and combustible liquids are the most predominant hazard classes involved. In the distribution by severe hazmat incidents also, the same classes of hazmat are involved, as shown in Table 3.4. The data is further classified by considering the amount of spillage of hazmat in each class by name of chemical. The spillage of combustible liquids is very high.

There are some surprising outcomes in the study of amount of spills of individual incidents. There are 386 incidents out of 1136 in which the amount of spill was zero (more than one-third), and 305 incidents where the spill was 1 gal or 1 lb. There were only 200 incidents with the amount of spill exceeding 10 gal or 10 lb. These results are displayed in the form of a bar-chart in Fig 3.1. It is known that HMIR reports only those incidents in which a spill has taken place. However, we find that 80% of the

Table 3.1

DISTRIBUTION OF HAZMAT ACCIDENTS IN PENNSYLVANIA
BY FAILURE TYPE - HMIR DATA* - 1983-1987

Failure type	Number of incidents (%)	Number of severe incidents (%)
Traffic accidents	62 (5.5)	33 (56.9)
Body or tank failure	228 (20.1)	6 (10.3)
Valve or fitting failure	430 (37.9)	9 (15.5)
Cargo shifting	350 (30.8)	3 (5.2)
Fumes or venting	1 (0.09)	1 (1.7)
Other	65 (5.7)	6 (10.3)
Total	1136	58

*On highway Incidents only

Table 3.2

DISTRIBUTION OF HAZMAT ACCIDENTS IN PENNSYLVANIA
BY CAUSE OF FAILURE - HMIR DATA* - 1983-1987

Cause of failure	Number of incidents (%)	Number of severe incidents (%)
Traffic accidents	62 (5.5)	33 (56.9)
Human error	638 (56.2)	9 (15.5)
Package failure	420 (37.0)	15 (25.9)
Other	16 (1.4)	1 (1.7)
Total	1136	58

*On highway incidents only

Table 3.3

DISTRIBUTION OF HAZMAT INCIDENTS IN PENNSYLVANIA
BY MATERIAL RELEASED - HMIR DATA* - 1983-1987

Material	Number of incidents (%)	Incidents caused by traffic accidents (%)	Incidents due to other causes (%)
ORM-A	7 (0.6)	0 (0.0)	7 (0.65)
ORM-E	18 (1.6)	6 (9.7)	12 (1.1)
Organic peroxide	10 (0.9)	0 (0.0)	10 (0.9)
Combustible liquid	38 (3.3)	15 (24.2)	23 (2.1)
Flammable liquid	449 (39.5)	26 (41.9)	423 (39.4)
Flammable solid	3 (0.26)	0 (0.0)	3 (0.2)
Oxidizer	55 (4.8)	0 (0.0)	55 (5.1)
Non flammable	10 (0.9)	0 (0.0)	10 (0.9)
Flam. Comp. Gas	11 (0.9)	1 (1.6)	10 (0.9)
Poisonous Gas-B	55 (4.8)	1 (1.6)	54 (5.1)
Radioactive material	1 (0.09)	0 (0.0)	1 (0.09)
Explosive class-B	1 (0.09)	0 (0.0)	1 (0.09)
Corrosive material	478 (42.1)	12 (19.4)	466 (43.4)
Total	1136	62	1074

*On highway incidents only

Table 3.4

DISTRIBUTION OF SEVERE HAZMAT INCIDENTS IN PENNSYLVANIA BY MATERIAL RELEASED - HMIR DATA* - 1983-1987

Material	Number of incidents (%)	Incidents caused by traffic accidents (%)	Incidents due to other causes (%)
ORM-A	0 (0.0)	0 (0.0)	0 (0.0)
ORM-E	2 (3.4)	2 (6.06)	0 (0.0)
Organic peroxide	0 (0.0)	0 (0.0)	0 (0.0)
Combustible liquid	10 (17.2)	9 (27.3)	1 (4.0)
Flammable liquid	17 (29.3)	14 (42.4)	3 (12.0)
Flammable solid	1 (1.7)	1 (3.0)	0 (0.0)
Oxidizer	0 (0.0)	0 (0.0)	0 (0.0)
Non flammable	1 (1.7)	0 (0.0)	1 (4.0)
Flam. Comp. Gas	3 (5.2)	1 (3.0)	2 (8.0)
Poisonous Gas-B	3 (5.2)	0 (0.0)	3 (12.0)
Radioactive material	0 (0.0)	0 (0.0)	0 (0.0)
Explosive class-B	0 (0.0)	0 (0.0)	0 (0.0)
Corrosive material	15 (25.8)	3 (9.1)	12 (48.0)
Others	6 (10.3)	3 (9.1)	3 (12.0)
Total	58	33	25

*On highway incidents only

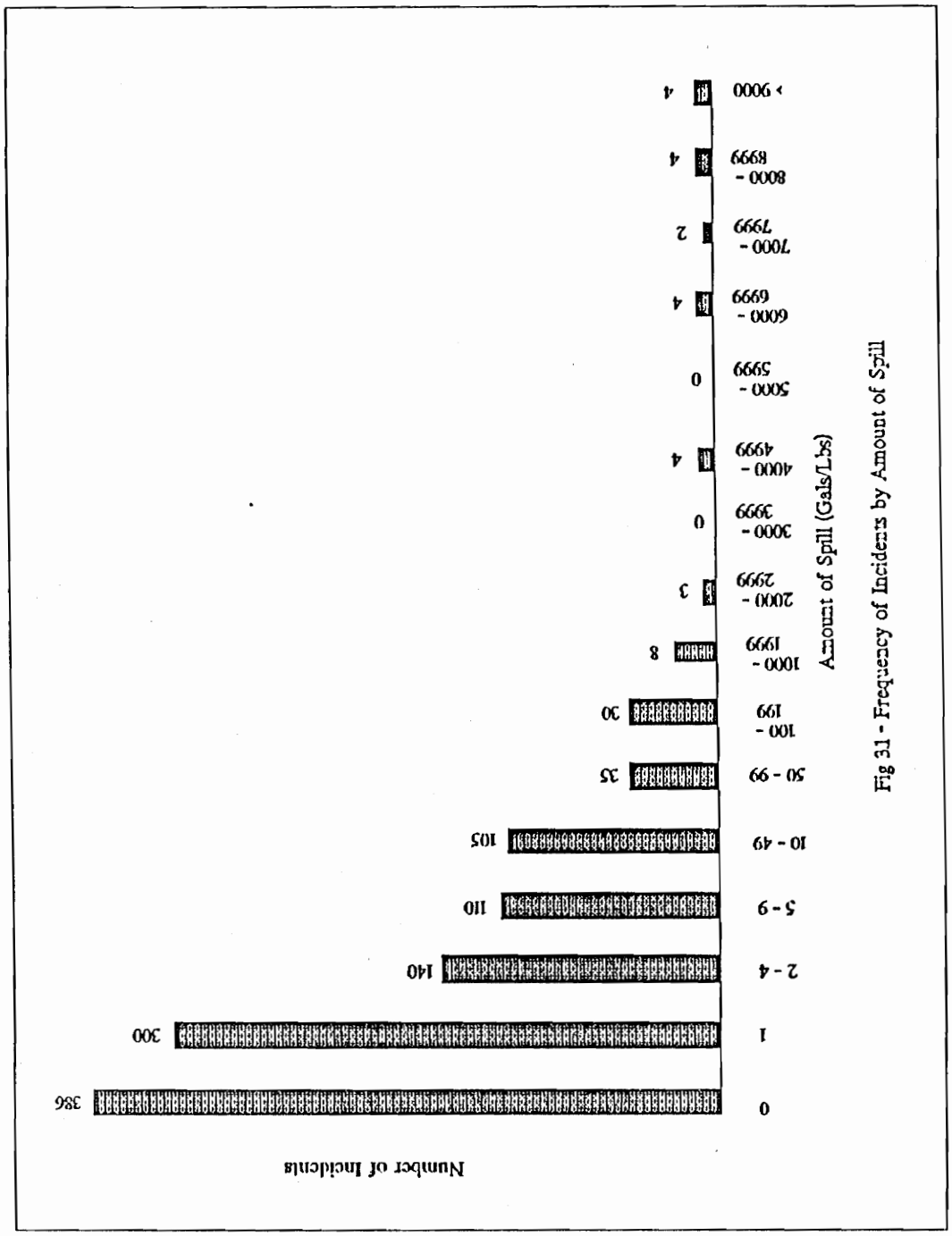


Fig 31 - Frequency of Incidents by Amount of Spill

incidents have insignificant spills. This raises questions of underreporting of spill data.

The causes and effects of high volume spills (spills greater than 1000 gal or 1000 lbs) were investigated. There were 29 instances of spills greater than 1000 gal or 1000 lbs. Of them 25 (86.2%) were caused by traffic accidents. There were six instances, all due to traffic accidents in which, there was a fire or explosion, or both, in addition to spillage. This clearly shows that serious consequences are primarily due to traffic accidents even though traffic accidents, are responsible for only 5.5% of all incidents in the HMIR data and the probability of the event occurring is low. The most common hazmat involved in those spills were gasoline and other flammable liquids and hazardous waste.

3.1.3 Consequences of Incidents

Table 3.5 shows a summary of consequences of hazmat incidents reported to HMIR during the period 1983-87. A total of three deaths has occurred on highway during this period, all of them being the result of traffic accidents. The average number of deaths per incident is 0.0026 or one death per 385 incidents. The number of injuries is 17 with the average being 0.015 per incident or 1 injury per 67 incidents. The average property damage is $ 2170 per incident.

Table 3.5

SUMMARY OF CONSEQUENCES OF HAZMAT INCIDENTS
IN PENNSYLVANIA - HMIR DATA* - (1983-1987)

	Number of incidents	Incidents caused by traffic accident	Incidents caused due to other causes
Number of incidents	1136	62	1074
Number of fatalities	3	3	0
Fatalities/incident	0.0026	0.048	
Number of injuries	17	1	16
injuries/incident	0.015	0.016	0.015
Total property damage ($)	2463290	1690242	773048
Property damage/incident	2170	27260	720

*On highway incidents only

3.2 *Analysis of Bureau of Motor Carrier Safety Data*

The accident data obtained from Bureau of Motor Carrier Safety (BMCS) for the state of Pennsylvania for the years 1983-1987 was analyzed. As mentioned earlier, BMCS database has reports of truck accidents, and also has information as to whether or not a hazmat carrying truck was involved and whether or not a release occurred during the accident.

3.2.1 Type of Cargo Involved

Table 3.6 shows the distribution of BMCS reported truck accidents by type of cargo. Of all truck accidents reported, 35.2% had general freight, 21.4% were empty and 3.8% were carrying liquids in bulk. However, in accidents in which a release occurred the distribution by cargo type is totally different. In this case, 60.7% of releases were from vehicles which carried liquids in bulk and 21.4% of releases were from vehicles which carried general freight as cargo.

3.2.2 Highway Type and Area Type

Table 3.7 shows the distribution of truck accidents by highway type and area type. About 63.3% of all truck accidents and hazmat carrying truck accidents occur in rural areas. Business areas the next most predominant areas of accident occurrence with about 28.8% of accidents. Also note that 57.7% of all accidents involving a release

Table 3.6

DISTRIBUTION OF BMCS REPORTED TRUCK ACCIDENTS
IN PENNSYLVANIA BY CARGO TYPE (1986-1987)

Cargo type	All truck accidents (%)	Accidents involving Hazmat carrying trucks			
		Combined(%)	No release (%)	Hazmat release (%)	Percent of release in Hazmat acc.
General freight	1273 (35.2)	40 (24.8)	34 (25.6)	6 (21.4)	15.0
Gases in bulk	8 (0.2)	5 (3.1)	4 (3.0)	1 (3.6)	20.0
Solids in bulk	77 (2.1)	3 (1.9)	2 (1.5)	1 (3.6)	33.3
Liquids in bulk	138 (3.8)	80 (49.7)	63 (47.4)	17 (60.7)	21.3
Explosives	1 (0.03)	1 (0.6)	0 (0.0)	1 (3.6)	100.0
Empty	773 (21.4)	2 (1.2)	2 (1.5)	0 (0.0)	0.0
Others	1350 (37.3)	30 (18.6)	28 (21.1)	2 (7.1)	6.7
Total	3620	161	133	28	17.4

Table 3.7

DISTRIBUTION OF BMCS REPORTED TRUCK ACCIDENTS
IN PENNSYLVANIA BY HIGHWAY TYPE AND AREA TYPE (1986-1987)

	All truck accidents (%)	Accidents involving Hazmat carrying trucks			
		Combined (%)	No release (%)	Hazmat release (%)	Percent of release in Hazmat acc.
Rural areas					
1 - lane	126 (3.7)	2 (1.3)	1 (0.8)	1 (3.9)	50.0
2 - lane	784 (22.9)	43 (28.1)	38 (29.9)	5 (19.2)	11.6
3 - lane	106 (3.1)	6 (3.9)	4 (3.2)	2 (7.7)	33.3
4 - lane or more	1150 (33.6)	46 (30.1)	39 (30.7)	7 (26.9)	15.2
Subtotal	2166 (63.3)	97 (63.4)	82 (64.6)	15 (57.7)	15.5
Business areas					
1 - lane	78 (2.3)	2 (1.3)	0 (0.0)	2 (7.7)	100
2 - lane	387 (11.3)	17 (11.1)	14 (11.0)	3 (11.5)	17.6
3 - lane	81 (2.4)	4 (2.6)	4 (3.2)	0 (0.0)	0.0
4 - lane or more	397 (11.6)	21 (13.7)	18 (14.2)	3 (11.8)	14.3
Subtotal	943 (27.6)	44 (28.8)	36 (28.3)	8 (30.8)	18.2
Residential areas					
1 - lane	29 (0.8)	0 (0.0)	0 (0.0)	0 (0.0)	0.0
2 - lane	179 (5.2)	9 (5.9)	6 (4.7)	3 (11.5)	33.3
3 - lane	18 (0.5)	0 (0.0)	0 (0.0)	0 (0.0)	0.0
4 - lane or more	85 (2.5)	3 (2.0)	3 (2.4)	0 (0.0)	0.0
Subtotal	311 (9.1)	12 (7.8)	9 (7.1)	3 (11.5)	25.0
Total	3420	153	127	26	17.0

occurred in rural areas, followed by business areas with 30.8% and residential areas with 11.5%.

3.2.3 Accident Type

Table 3.8 shows the distribution of accidents by accident type. Considering total accidents, collision with passenger car is the most common accident type with 38.5% of all accidents followed by collision with truck (17.8%) and collision with fixed object (11.3%). The most common non-collision accidents are overturn with 8.2%, jackknife with 6.7% and ran-off-road with 5.5% of all accidents.

In accidents involving hazmat carrying trucks, collision with passenger car is the most common (41.7%) followed by collision with truck (14.3%) and overturn (12.5%). However, of the accidents in which a release occurred non-collision accidents are more predominant with about 64.2% of accidents. Overturn is the major non-collision accident type with 41.8% of accidents resulting in release.

3.2.4 Consequences of Accidents

A total of 318 deaths and 3751 injuries occurred in all BMCS reported truck accidents in Pennsylvania for the years 1986-1987. Of these, the number of deaths and injuries that occurred due to accidents involving hazmat carrying trucks was 24 and 178 respectively. Further distribution of these consequences is shown in Table 3.9. Note that accidents involving hazmat release are likely to cause more deaths than those involving no release of hazmat. However, it is not possible to determine

Table 3.8

DISTRIBUTION OF BMCS REPORTED TRUCK ACCIDENTS
IN PENNSYLVANIA BY ACCIDENT TYPE (1986-1987)

Accident type	All truck accidents(%)	Accidents involving Hazmat carrying trucks			
		Combined(%)	No release (%)	Hazmat release(%)	Percent of release in Hazmat acc.
SINGLE VEHICLE ACCIDENTS					
Non-collision accidents					
Ran off road	194 (5.5)	14 (8.3)	12 (8.6)	2 (7.1)	14.3
Jackknife	237 (6.7)	5 (3.0)	3 (2.1)	2 (7.1)	40.0
Overturn	288 (8.2)	21 (12.5)	9 (6.4)	12 (42.9)	57.1
Separation of units	10 (0.3)	0 (0.0)	0 (0.0)	0 (0.0)	0.0
Fire	22 (0.6)	0 (0.0)	0 (0.0)	0 (0.0)	0.0
Cargo spillage	10 (0.3)	3 (1.8)	1 (0.7)	2 (7.1)	66.7
Cargo shifting	12 (0.3)	1 (0.6)	1 (0.7)	0 (0.0)	0.0
Other non collision	5 (0.1)	4 (2.4)	4 (2.9)	0 (0.0)	0.0
Collision accidents					
Collision with fixed object	398 (11.3)	7 (4.2)	7 (5.0)	0 (0.0)	0.0
Collision with parked object	227 (6.4)	10 (6.0)	9 (6.4)	1 (3.6)	10.0
collision with train	10 (0.3)	0 (0.0)	0 (0.0)	0 (0.0)	0.0
collision with non-motorist	84 (2.4)	1 (0.6)	0 (0.0)	1 (3.6)	100.0
other collision	11 (0.3)	7 (4.2)	5 (3.6)	2 (7.1)	0.29
MULTIPLE VEHICLE ACCIDENTS					
Collision with passenger car	1361 (38.5)	70 (41.7)	68 (48.6)	2 (7.1)	2.9
collision with truck	627 (17.8)	24 (14.3)	20 (14.3)	4 (14.3)	16.7
collision with other vehicle type	35 (1.0)	1 (0.6)	1 (0.7)	0 (0.0)	0.0
Total	3531	168	140	28	16.7

the actual cause of deaths or injuries, i.e., whether caused due to hazmat release or due to accident etc.

3.3 Analysis of Penn. DOT Traffic Accident Data Involving Hazardous Substance

The traffic accident data of Pennsylvania for the years 1986-1987 provided by the Bureau of Accident Analysis, Penn DOT, has also been analyzed. This data has information about the accidents in which a hazardous substance was involved. There is no information in the database as to whether or not a release took place during an accident.

3.3.1 Type of Cargo Involved

Table 3.10 shows the distribution of truck accidents involving hazardous substance by type of cargo. Fuel oil and gasoline are the most predominant cargoes involved in traffic accidents (42.1%) followed by flammable liquid (10.0%) and corrosive material (7.0%). In most of the fatalities the same cargoes mentioned above are involved (63.7% of total fatalities). Only some important materials which have been considered in HMIR and BMCS database analyses are listed in the table, others have been aggregated.

Table 3.9

SUMMARY OF CONSEQUENCES OF BMCS REPORTED TRUCK ACCIDENTS IN PENNSYLVANIA (1986-1987)

	All truck accidents	Accidents involving Hazmat carrying trucks		
		Combined	No release	Hazmat release
Number of accidents	3631	168	140	28
Number of fatalities	318	24	17	7
Fatalities per accident	0.088	0.143	0.121	0.25
Number of injuries	3751	178	158	20
Injuries per accident	1.033	1.06	1.129	0.714
Total property damage	11836734	539575	470275	69300
Property damage per accident	2360	3212	3360	2475

Table 3.10

DISTRIBUTION OF HAZMAT ACCIDENTS IN PENNSYLVANIA
BY CARGO TYPE - PENN.DOT DATA* - 1986-1987

Cargo type	Number of accidents	Number of fatalities (%)	Number of injuries (%)
Organic peroxide	0 (0.0)	0 (0.0)	0 (0.0)
Gasoline	75 (13.2)	6 (18.2)	65 (13.2)
Fuel oil	165 (28.9)	3 (9.1)	106 (21.5)
Flammable liquid	57 (10.0)	10 (30.3)	51 (10.3)
Flammable solid	5 (0.9)	1 (3.0)	4 (0.8)
Oxidizer	10 (1.8)	1 (3.0)	8 (1.6)
Non-flammable gas	29 (5.1)	1 (3.0)	26 (5.3)
Poison gas	6 (1.0)	0 (0.0)	11 (2.2)
Radioactive mat.	8 (1.4)	0 (0.0)	3 (0.6)
Explosive-A	7 (1.2)	0 (0.0)	8 (1.6)
Explosive-B	3 (0.5)	0 (0.0)	5 (1.0)
Corrosive mat.	40 (7.0)	2 (6.1)	40 (8.1)
Other	165 (28.9)	9 (27.3)	166 (33.7)
Total	570	33	493

*Involving hazardous substance

3.3.2 Highway Factors

The distribution of traffic accidents involving hazmat for 1986-1987 by highway class is presented in Table 3.11. Most of the accidents take place on US or State highways (64.7%) followed by municipal street or township roads (16.5%) and interstate highways (16.0%). Also, most of the fatalities and injuries due to these accidents occur on US or State highways.

Table 3.12 shows the distribution of hazmat accidents in Pennsylvania by "relationship to junction". About 32.5% of all hazmat accidents take place right at the intersections, 0.3% take place at railroad crossings, the rest occurring at other places such as midblocks, highway sections, ramps, etc.

3.3.3 Accident Type

In Table 3.13, distribution of hazmat accidents in Pennsylvania by accident type and manner of collision is shown. The following accident types are the most common.

- Rear end multiple vehicle collision (26.7%)
- Angle multiple vehicle collision (22.8%)
- Collision with fixed object (19.1%)
- Non Collision accidents (10.2%)
- Head on collision (8.9%)

Table 3.11

DISTRIBUTION OF HAZMAT ACCIDENTS IN PENNSYLVANIA
BY HIGHWAY CLASS - PENN.DOT DATA* - 1986-1987

Highway class	Number of accidents (%)	Number of fatalities (%)	Number of injuries (%)
Interstate	91 (16.0)	4 (12.1)	85 (17.2)
US or State Highway	369 (64.7)	27 (81.8)	330 (66.9)
County road	4 (0.7)	0 (0.0)	1 (0.2)
Municipal street and township road	94 (16.5)	1 (3.0)	69 (14.0)
Other	12 (2.1)	1 (3.0)	8 (1.6)
Total	570	33	493

*Involving hazardous substance

Table 3.12

DISTRIBUTION OF HAZMAT ACCIDENTS IN PENNSYLVANIA
BY RELATIONSHIP TO JUNCTION - PENN.DOT DATA* - 1986-1987

Relationship to junction	Number of accidents (%)	Number of fatalities (%)	Number of injuries (%)
None	383 (67.2)	21 (63.6)	322 (65.3)
Intersection	185 (32.5)	12 (36.4)	168 (34.1)
Railroad crossing	2 (0.3)	0 (0.0)	3 (0.6)
Total	570	33	493

*Involving hazardous substance

Table 3.13

DISTRIBUTION OF HAZMAT ACCIDENTS IN PENNSYLVANIA
ACCIDENT TYPE AND MANNER OF COLLISION
PENN.DOT DATA* 1986-1987

Accident type and manner of collision	Number of accidents	Number of fatalities	Number of injuries
Single vehicle			
Non collision accidents	58 (10.2)	4 (12.1)	29 (5.9)
Collision accidents			
Hit fixed object	109 (19.1)	2 (6.1)	75 (15.2)
Hit pedestrian	8 (1.4)	1 (3.0)	8 (1.6)
Multiple vehicle			
Head-on	51 (8.9)	14 (42.4)	61 (12.4)
Rear-end	152 (26.7)	1 (3.0)	163 (33.1)
Side swipe	49 (8.6)	0 (0.0)	33 (6.7)
Angle	130 (22.8)	11 (33.3)	118 (24.0)
Other collisions	13 (2.3)	0 (0.0)	6 (1.2)
Total	570	33	493

*Involving hazardous substance

3.3.4 Summary of Consequences

Table 3.14 presents a summary of consequences of accidents involving hazardous substance in Pennsylvania. A total of 570 hazmat accidents have occurred resulting in 33 fatalities and 493 injuries (i.e., 0.058 fatalities/accident and 0.865 injuries/accident).

Table 3.15 shows a distribution of accidents involving hazmat in Pennsylvania by severity of accident between the years 1986-1987. Severity of accident is the consequence associated with the accident - fatalities, injuries, and property damage. Of the 570 accidents reported, 29 were fatal, 324 accidents had resulted in injuries and 217 accidents had property damage only as the result of accident.

3.4 Summary

The summary of the results of analysis of accident/incident databases is presented here.

3.4.1 HMIR Data

About 60% of all hazmat incidents occur on highway. The predominant failure type is valve or fitting failure followed by body or tank failure. Most of the hazmat incidents are caused by human error which does not result in severe incidents. Traffic accidents are responsible for only 5.5% of all incidents. However, they are the

Table 3.14

SUMMARY OF CONSEQUENCES OF ACCIDENTS INVOLVING HAZARDOUS SUBSTANCE - PENN.DOT DATA* - 1986-1987

Number of accidents	570
Number of fatalities	33
Fatalities per accident	0.058
Number of injuries	493
Injuries per accident	0.865

*Involving hazardous substance

Table 3.15

DISTRIBUTION OF HAZMAT ACCIDENTS BY SEVERITY OF ACCIDENT - PENN.DOT DATA* - 1986-1987

Accident severity	Number of accidents
Fatal accidents	29 (5.1)
Injury accidents	324 (56.8)
Property damage	91 (38.1)
Total	570

*Involving hazardous substance

main causes of severe hazmat incidents - about 57% of them being attributable to them.

The most common classes of hazardous materials released are flammable and combustible liquids. The types of materials involved in huge volume spills of hazmat belong to the combustible liquid class, with gasoline being the most predominant. Most of the large volume spills are caused by traffic accidents. Of the large spills, 6 cases resulted in fire or explosion. There were 386 incidents in which the amount of spillage is zero, an indication of under-reporting of data.

Cargo tanks are the most common type of containers involved in spillage of hazmat especially when the quantity of spill is considered. There were 5 cases of fire as a result of spillage of hazmat from cargo tanks.

Hazmat incidents, caused by vehicular accidents, were found to cause more deaths, injuries, and property damage than those due to other causes.

3.4.2 BMCS Data

Hazmat carrying trucks are involved in 4.5% of all truck accidents. Overall, 20% of accidents involving hazmat carrying vehicles resulted in release.

Approximately, 60% of all accidents involving hazmat carrying trucks take place in "daylight" and 35% during "dark-not-lighted" conditions. About 54% of accidents involving release of hazmat occur in "day light" and 38.5% during "dark-not-lighted" conditions.

In accidents involving hazmat release, 60.7% of vehicles had liquids in bulk and 21.4% had general freight as cargo. About 57.7% of all accidents involving a release

occurred in rural areas, followed by business areas with 30.8% and residential areas with 11.5%.

Of all accidents involving hazmat, collision with passenger car (41.7%) is the most common accident type, followed by collision with truck (14.3%) and overturn (12.5%). Overturn is primary accident type resulting in release of hazmat accounting for 42.9% of all hazmat release accidents. In hazmat accidents in which a release occurred, 82.8% of trucks were of single trailer combination. The accidents involving hazmat release are more likely to cause more deaths than those involving no release of hazmat.

3.4.3 Penn DOT Data Involving Hazardous Substance

Most of the accidents (and fatalities and injuries) take place during daylight (68.2%) followed by dark-not-lighted conditions (16.1%) and dark-lighted condition (10.7%). Fuel oil and gasoline are the most predominant cargoes involved with 42.1%, followed by flammable liquid (10.0%) and corrosive material (7.0%).

Most of the accidents take place on US or State Highways (64.7%) followed by municipal street or township roads (16.5%) and interstate highways (16.0%). About 61.4% of hazmat accidents occur on dry surface conditions, 23.2% in wet conditions and 15.4% on ice or snow.

Rear-end multiple vehicle collision is the most common accident type (26.7%), followed by angle collisions (22.8%), and collision with fixed object (19.1%). However, head-on collision cause maximum number of fatalities (42.4%) followed by angle collisions (33.3%) and non collision accidents (12.1%). The number of fatalities per accident is 0.058 and the number of injuries per accident is 0.865.

In order to obtain measures to mitigate risk, the incident data is important. This would give an idea about the type of accidents to be reduced and require attention. If it is clearly known that "overturn" causes the maximum number of spills of hazardous materials, then one of the objectives of mitigation measures is to reduce those accidents. However, this was not possible because, it was found through the analysis of databases that the number of accidents were too few to make such conclusions. Hence, the original objective has been changed to "improving highway geometric elements," as it is more general approach and capable of reducing accidents in general. Specific measures can still be considered if conditions appear to warrant them.

The consequences of an incident plays a much larger role in the risk analysis. In order to determine the consequences, we need the impact area associated with the particular hazardous material being considered. From the database analysis, we know the volume of spill of individual chemicals. This must be estimated to obtain the impact area of different materials [28].

In the development of mitigation measures, an expert system type approach has been adopted because of the ambiguous nature of databases and also because there is no clear definition of a "catastrophic event". For example, we could infer from the analysis of the databases that "overturn" is the major cause of hazmat accidents. However, the catastrophic nature of the accident would be different based on the location and type of exposure. It was decided that the expert system approach used by the Kansas State University study would be adopted, wherein a set of catastrophic scenarios were defined and then mitigation measures considered. These comprise a set of wide ranging possibilities to be considered as a starting point.

In the following sections an overview of the methodology to determine risk and develop mitigation measures is presented.

4.0 OVERVIEW OF THE RISK MODEL

This section provides an overview of the proposed risk assessment model and vulnerability evaluation. It is an updated and improved version of the risk model that is part of the FHWA routing guide [11]. The basic risk assessment formula is:

$$Risk = Probability \times Consequence \tag{4.1}$$

The consequences are expressed in terms of exposure of people, property, environment etc. The above formula is rewritten using the notation as:

$$RISK_i = P(R)_i \times (CONSEQUENCE_i / L_i) \times IW \tag{4.2}$$

where

$RISK_i$ = Risk along a segment i

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

L_i = Length of route segment i (mi)

IW = Impact width of a hazardous material

The consequence is divided by length of segment in order to avoid double counting. This will be evident from the equation used to determine probability of accident. There are three steps involved in the determination of risk using this model:

1. Determine Accident Probability

2. Determine Accident Consequence
3. Calculate Risk.

4.1.1 Determine Accident Probability

The probability of a hazmat incident is calculated with the following equation :

$$P(R)_i = TAR_i \times P(R/A)_i \times L_i \qquad (4.3)$$

where

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

TAR_i = Truck accident rate (accident 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 of route segment i (mi)

4.1.1.1 Truck Accident Rate, TAR

Since the calculation of TAR_i plays a major role in determining probability, it should be understood clearly. The values of TAR_i is based on three different options depending on data. These are:

- Hazmat truck accidents
- All truck accidents
- Default value.

The risk obtained from first option is referred to in this study as as **Observed Risk,** while the risk from the other options is **Potential Risk.** The *TAR* for the first two options can be obtained using the following equation:

$$TAR_i = \frac{Number\ of\ accident_i}{TADT_i \times \%\ Truck \times 365 \times years \times L_i} \qquad (4.4)$$

where

TAR_i = Truck accident rate (accident per veh-mi) for segment i

$Number\ of\ accident_i$ = Number of accidents in chosen option for segment i

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

$\%\ Truck$ = Percent of truck flow segment i (If all truck option is considered, the value is 1)

$Years$ = Duration of study period

L_i = Length of segment i (mi)

The last option, default value is based on existing data at the national level stratified by **area type** and **highway type**. The area type and highway type for these default values will be divided into the following categories.

- Rural freeways
- Rural divided highways
- Rural two lane two way highways (Rural undivided highway)
- Urban freeways
- Urban arterial streets

4.1.1.2 Probability of Release, P(R/A)

The second term, $P(R / A)_i$ for different area type and highway type will be adapted from the national default values developed by MRI [11]. This is acceptable since the probability of a hazmat release for a specific highway and area type is assumed to be not dependent on site-specific route characteristics. Moreover, data for obtaining this value is available only in three states in the United States. The default value of probability of release for different area types and highway types are shown in Table 4.1.

4.1.1.3 Length, L

The length of segment is considered because of its direct relevance to the exposure of vehicles to risk of accidents. If a segment is twice as longer than the other segment, then the risk is twice on the longer segment given the other conditions are same.

At this juncture, a highly-reliable historical data for specific route can be used. However, an option is available to the user to check the significance of the data by a simple Chi-squared text. So, the users have three options to perform the probability.

1. Use site-specific accumulative historical value (options 1 & 2 in TAR)
2. Use site-specific default value
3. Use Chi-squared method to select one of the two options.

Before using specific data it should be tested by Chi-squared test. If not statistically valid, default should be used. However, it is not recommended to use default values

Table 4.1

PROBABILITY OF RELEASE BASED ON AREA TYPE AND HIGHWAY TYPE

Highway & Area Type	P(R/A)
Urban Freeway	0.062
Urban Arterial Highway	0.059
Rural Freeway	0.09
Rural Divided Highway	0.082
Rural Two-way Two-lane Highway	0.086

Source: Harwood, D.W., and E.R. Russell, "Present Practices of Highway Transportation of Hazardous Materials, Midwest Re

without taking historical data into consideration. The third option may be the most reasonable approach at this stage. It should be noted that as the duration of accident record increases, site-specific cumulative, historical data will become more reliable. However, a Chi-squared test should always be conducted.

The procedure of using a historical data and its validity with Chi-squared test as developed by MRI [11] will be summarized below:

- 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 default rates. The expected truck accident frequency can be computed as:

$$A_e = TAR \times TADT \times L \times 365 \times N \qquad (4.5)$$

where

A_e = expected truck accident frequency

TAR = expected truck accident rate based on default values in Table 4.1 (# accidents per veh-mi)

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

L = length of highway segment (mi)

N = duration of study period (yr)

- Step 3. If A_e is less than 5, the Chi-squared test is not applicable. So, the default or the site-specific value whichever is greater, should be used. If A_e is greater than or equal to 5, compute Chi-squared statistics as follows:

$$X^2 = \frac{(A_e - A_o)^2}{A_e} \qquad (4.6)$$

If X^2 is less than or equal to 4, then there is no significant difference between the expected and observed accident frequency at the 5% significance level. Here, default accident rates should be preferred as it is based on a larger sample. If X^2 is greater than 4, then the default and observed values differ significantly. If the site-specific accident rate is greater than the default accident rate, then use site-specific rate or vice-versa.

4.1.2 Determine Consequence

Ideally, consequences would mean persons killed, persons injured, property damage etc. However, predicting detailed, specific consequences of this nature is not practical with the current modelling approach and requires several assumptions that are open to criticism. Hence, consequence is measured in terms of persons, property etc. exposed to the release.

In most cases, government officials are mainly concerned with population exposure and property exposure. In this study, population exposure is divided into residential population and employment population. Also included in this research are environmental exposure and special facility exposure.

Therefore, five different consequences are considered:

- Residential population exposure
- Employment population exposure
- Property exposure
- Environment exposure
- Special facility exposure

Each of five different exposures can be estimated separately. However, the general exposure, considering all exposures, can be estimated using weighted values, defined by the user. The procedure used to determine population exposure is presented here as an example.

4.1.2.1 Residential and Employment Population Exposure

The population potentially exposed to a release can be estimated on the basis of residential population, employment population, motorist, or a combination of the three. The basic assumption is that the personal injury consequences of a hazmat release are proportional to the population potentially exposed to a release. The steps in determining exposed residential population are listed below:

1. Delineate the potential impact zone on census tract maps that include the area around the route segment in question. The extent of the potential impact zones is dependent on the class of hazardous material.
2. Determine the portion of each census tract located within the impact zone.
3. Multiply the census tract population by the proportion of the census tract within the impact zone.
4. Sum the exposed populations for all census tracts along the route segment.

4.1.3 Determine Risks

As defined earlier, risk is a product of the probability of a hazmat accident and consequence of accident and can be obtained using equation 4.2. The consequence

in the equation can be replaced by the required type of exposure to obtain the value of that type of risk.

4.2 Response Capability

Response can be treated as a subjective factor in performing vulnerability evaluation. However, this value is not considered in the mathematical formulation with risk to produce a vulnerability value since the result might misguide user if he/she relies on the number itself.

The response can be classified into three different elements as follows:

1. The number of fire companies trained and equipped for responding to a hazmat accident
2. The number of police cars
3. The number of ambulances

Another factor which is important in response is the time taken to respond. These data are compiled for all the counties considered in this study and attached to the results obtained from risk analysis.

High risk segments are identified through risk analysis and then analyzed to decide on mitigation measures. This is the objective of the next section of the report "Development of Mitigation Measures". It uses the same ideology i.e., risk is made up of *probability* and *consequence* . However, because of the complex nature of the hazmat accident and the various possible consequences, it is difficult to obtain an analytical mitigation model. This involves much more interaction with the user and

user's choice of the types of measures to be considered. This is because, in some cases it may be the "probability" part of the risk analysis which is important and in other cases it may be the consequence. This is entirely site-specific and requires a good knowledge of the segment and area around it. This research attempts to help the user in the process by providing guidelines for developing protective systems. Moreover, this research is limited to those systems which are a direct responsibility of the highway department. Hence, emergency response measures were not considered.

5.0 DEVELOPMENT OF MITIGATION MEASURES

5.1 Introduction

The responsibility and cost of providing hazmat safety measures have always been shared by a partnership of federal, state, and local governments, and industry. At present, a number of protective measures in the form of regulations are in effect in order to make hazardous materials transportation safer. These include such things as placarding, specifications of containers, rerouting etc. However, these are only a few of the many measures necessary. In order to reduce the probability of hazmat accidents, there should be some special improvements on highways. Measures should be available to reduce accident probability, reduce accident severity and/or mitigate spill consequences and facilitate emergency response.

Mitigation follows risk assessment and routing. During the risk analysis, risks on various highway segments are calculated using default values of accident rate (potential risk) or historical accident rate values (observed risk). Mitigation measures should usually be considered based on the potential risk value unless the observed risk value statistically significant. Based on the risk value, and the user's definition of "high risk", he/she can select the highway segment to be considered for mitigation of risk. Various alternatives for the improvement of highway segment is presented. The user has the opportunity to choose the measures that should be implemented.

The output of mitigation is a reduced risk value. The framework of this task is explained below.

5.2 *Frame-work*

This study attempted to identify, or flag, potentially high risk locations due to spills of hazardous materials, and to evaluate the alternatives that could be designed and implemented in order to reduce the risk. Appropriate type of roadway improvements for the safe transportation of hazmat trucks, and protective systems that might be incorporated into new or reconstructed highway segments to mitigate consequences, are presented for various generalized scenarios.

Thus the development of mitigation measures is in two stages:

1. Roadway improvements to increase truck safety
2. Protective systems to reduce risk due to spills of hazmat in extremely high risk situations or to mitigate potentially catastrophic consequences.

The first part refers to measures which involve reduction of truck accidents. This type of mitigation is important in areas where accidents occur frequently and can be attributed to highway geometric elements. During the analysis of Hazardous Materials Incident Report (HMIR) data, it was found that human error is the most predominant cause of hazmat accidents. However, marginal vehicle factors combined with marginal roadway, environmental, and human factors, often contribute to the outcome of the accidents. To minimize the accidents and their potential severity, future design and maintenance programs will warrant broader shoulders, flatter slopes, longitudinal center barriers, longer acceleration and deceleration

lanes, higher frictional surfaces, sufficient traffic control signs and devices, etc. All of these can be categorized under good, state-of-the-art geometric design considerations for trucks. It should be noted that, though these are recommended by American Association of State Highway and Transportation Officials (AASHTO), "A policy on Geometric Design of Highways and Streets, 1984", (also known as green book), a majority of design principles had considered passenger car movement. These should be upgraded to accommodate safer movement of trucks, particularly in the era of bigger, longer and more powerful trucks being allowed on the highways.

A review of current literature on geometric design considerations for large trucks was conducted and several geometry improvements are recommended as one phase of protective system development. It should be emphasized that these geometric improvements are in addition to AASHTO's minimums as prescribed by the green book. That is, it is assumed all practices as per the green book will be met and the recommended improvements considered in addition. All these measures will reduce the probability of hazmat accidents by reducing the truck accident rate.

In developing accident probability reduction measures, the movement of trucks in general is considered. This is due to unavailability of data specific to the movement of hazmat carrying trucks. In fact, there is very little literature specifically related to trucks in general. However, at the accident stage, the cargo carried by trucks does not play any role. It is only when the result of an accident is a release, that the effect of type of cargo is important. Thus, if a highway is found to be safe for the movement of trucks, then it is safe for the movement of hazmat carrying trucks. The surrounding population and environment plays a more prominent role in evaluating the potential consequences due to release of hazmat and would be a major deciding factor in determining the risk of a particular highway segment due to hazmat transportation and also in routing.

The second part of the protective system development consists of identifying the high risk situations along roadway segments and determining protective measures to mitigate the consequences due to hazardous material incidents. This will not cover the nearly infinite number of possible scenarios that might be encountered, nor will it give answers to site-specific scenarios. However, it will give the state planner/designer or administrator enough information to alert him/her to situations where there is high risk of catastrophic occurrence and to assist him/her in the decision-making process of determining whether a protective system is appropriate.

Currently, there are very few protective systems that appear to have clear cut merit in reducing hazmat spills and/or mitigating consequences. The main focus of protective system development has been in the following four areas:

1. Keeping the vehicle contained within the roadway system with barriers, berms etc.
2. Containment systems
3. Special attention to elevated freeways, depressed freeways, and ramps to and from these freeways
4. Bridges over waterways or watershed areas particularly in potable water supply areas.

Scenarios were developed, which will provide the basis of a check list of potentially catastrophic occurrences to which planners/designers need to be alerted. The development of the generalized, prioritized scenarios was based on an earlier work by Russell [23], where a framework was developed by which a state could develop "feasible, implementable, and practical" protective systems. An advisory panel of contacts from interested states was formed to assist in the task. This approach reflected the true concerns of the states. Through questionnaire survey of advisory panel members, a list of eleven generalized scenarios was arrived at. The

protective system ideas were then keyed to the generalized scenarios. The basis of this "shopping list" of protective system ideas was the same panel that was instrumental in developing the scenarios and represents the collective ideas of the states' personnel. These ideas were refined so that the results relate directly to Pennsylvania problems as determined by other part of this study. Protective Systems were expanded to include policy and regulatory measures, such as, alternate routing, increased enforcement, material delivery regulations (curfews, time restrictions etc.) and strategies to decrease exposed population numbers.

The study considered the "practicability" of a protective system involving an analysis in the value of specific reduced risk value or percent reduction. It was concluded that the "practicability" had to be decision by state decision maker based on their perception of risk and the benefits of risk reduction. The effects of the above improvements on accidents and/or spill consequence mitigation were considered. However, these are new concepts and there is insufficient database history to quantify the effects of these improvements. The effectiveness of several types of improvements to highway design elements are available in terms of accident reduction factors for all vehicles. These were used because there is no data on the effect of these improvements specifically related to truck accident reduction. The effectiveness of protective systems to reduce consequences are not available, again because of insufficient history. Many of these concepts and developments are very recent and hence the decision to implement can be only judgmental. This process was used by a panel who rated various protective systems by giving a value of the percent risk reduction to each of these improvements. These values serve as a starting point to assist state decision maker in their determination of the effectiveness of protective systems. The user is encouraged to use better values of risk reduction

for the specified improvements, when available and to keep records to document their effectiveness when improvements and/or protective systems are implemented.

This work is presented in following parts:

1. Probability reduction
   - Geometric design check.
   - Effectiveness of geometric design improvements.
2. Consequence reduction
   - Development of scenarios and protective systems.
   - Effectiveness of the protective systems.

Finally a summary of a suggested decision-making methodology to decide on protective systems on highway segments is presented. This starts with check-lists of various improvements to be considered.

The above parts constitute a frame-work by which the measures to mitigate risk due to hazmat can be formulated. It is to be noted that there is little or no data on protective systems at present and the framework has to be modified and refined as the technology improves. However, this study forms a basis for such improvements.

5.3 *Probability Reduction*

5.3.1 Geometric Design Check

Geometric design check is the first stage of mitigation. The intent here is to reduce accident probability and/or mitigate the severity of accident, thereby reducing

the probability of a hazmat incident. Though there are a number of factors which contribute to an accident and associated release, this research is limited to considering improvements which are responsibility of highway department only. The factors such as driver behavior, environmental factors etc. are beyond our control and hence are not addressed. However, steps need to be taken to enforce basic traffic laws and whatever regulatory measures are in effect. In cases where accidents are difficult to control, the objective here is to make sure that the contribution of highway elements towards the severity of accident is minimal.

There are a number of geometric elements on highways that influence accident probability. The design considerations of these elements are determined by AASHTO [1]. However, the characteristics of trucks have not been adequately represented in it. In determining the geometry, the type, size, weight, gradability, acceleration, deceleration and turning features of trucks all play an important role.

In this section, some geometric design elements requiring special attention to facilitate movement of trucks and to reduce truck accidents are addressed. This has been obtained through literature review of various studies conducted addressing this problem. It is emphasized that, the segment under consideration should be checked with the geometric design elements identified here and should meet all the necessary requirements as specified by AASHTO. This would further ensure the safe movement of trucks.

The relationship between geometric design elements and accident types was also studied. If it is found that a highway segment has an unusually high number of a particular type of accident, then related geometric elements should be studied and improvements considered.

The main features of trucks demanding attention is their size, weight, and wheel-base. The size and weight of trucks are important factors in lane and shoulder

design considerations whereas the wheel-base influences the alignment due to off-tracking problems. The following geometric design elements were identified as having significant bearing on truck safety [8, 27, 30]:

- Lane width
- Shoulder width
- Shoulder type
- Degree of curvature
- Sight distance
- Bridge width
- Vertical grade
- Clear roadside
- Median/median barrier.

All these are addressed individually with specific reference to trucks and accident type and the safe design considerations for movement of trucks.

5.3.1.1 Lane and Shoulder Width and Type

Wide lanes and shoulders provide the drivers with increased opportunity for safe recovery when their vehicles start to run off the road (an important factor in single vehicle accidents) and increased lateral separation between overtaking and meeting vehicles (an important factor in side swipe and head on accidents).

AASHTO states that on rural two-way highways, hazardous conditions exist on pavements that are less than 22 ft wide when even a moderate volume of mixed traffic is present because of inadequate body clearance [1]. In experiments conducted in earlier days it was found that the drivers of passenger cars prefer a clearance of about 5 ft when meeting other vehicles. This would render the 20 ft pavements

inadequate for safe movement of passenger cars with commercial traffic. AASHTO has recommended a lane width of 11-13 ft. However, a lane width of 12 ft can be considered safe. If the lane width is less than 12 ft, then it may be necessary to control the number and movement of commercial vehicles.

Wide shoulders result in reduced interruption from emergency use, stopped vehicles and roadside maintenance activities, improved sight distance at critical horizontal curves, as well as lateral support of pavement base and surface courses. Adequate shoulder width also increases the opportunity of safe recovery when vehicles start to run off the road. This is of particular concern among large combination trucks, which have a higher incidence of single vehicle accidents than do passenger cars.

In order to accommodate stopped vehicles, AASHTO recommends that vehicles should clear the pavement edge by at least 1 ft and that a 2 ft working space should be provided. AASHTO recommends that, for heavily traveled and high-speed highways, the usable shoulder width should be at least 10 ft, but preferably 12 ft [1].

The type of shoulder is also critical for safe operation of trucks because of off-tracking problems and the likelihood of rollover if the truck wheels leave the pavement edge. Paved shoulders alleviate these problems. Also, drop-offs at the pavement edge are less prevalent where there are paved shoulders. According to prior research the following conclusions have been found:

- Accident rates decrease with increases in lane and shoulder width;
- In terms of accident reduction per foot of added width, widening lanes has a bigger payoff than widening shoulders; and
- Stabilized shoulders (paved) have lower accident rates than unstabilized (unpaved) shoulders [29].

Previous research findings indicate that increasing lane and shoulder width reduce certain types of accidents. Increasing lane and shoulder width is found to cause significant reduction of run-off-road and opposite direction accidents. The effectiveness of shoulder type in terms of specific accident reduction is not known. However, paved shoulders have lower accident rates than unpaved shoulders [36].

5.3.1.2 Degree of Curvature

Highway curves have been found to exhibit higher accident rates than tangent sections, and the accident rate increases as the degree of curvature increases. Sharp curves are typically found in areas with topographical constraints, which result in roadway designs with narrow lane widths and limited shoulders, and are often accompanied by steep grades; these design features are known to contribute to roadside encroachments [29, 30].

Two operating characteristics of large trucks cause particular problems. The drivers may have difficulty in steering their vehicles in the center of the lane and long trucks occupy more space while negotiating sharp curves because of off-tracking problems or lateral displacement of the rear portion of the trailer.

The extent of off-tracking depends on the geometry of the curve - shorter radii and larger turn angles increase the amount of off-tracking, and the dimensions of the vehicle. Curves should be smooth with long radii, i.e., with low degree of curvature, so that the problems of off-tracking are minimum.

5.3.1.3 Sight Distance

Adequate sight distance has to be provided along the highway, so that drivers can control their vehicles to avoid collision with other vehicles and objects that conflict with their path. This is a function of operating speeds and is achieved by designing non-restrictive horizontal and vertical alignment and by avoiding sight obstructions (vegetation, embankments, wall, etc.).

Trucks generally require longer braking distances, but because truck drivers are able to see the vertical features of obstructions substantially further ahead because of the higher position of the seat in the vehicle, separate stopping sight distances for automobiles and trucks are not used in highway design standards. However, it was found that the drivers of large trucks are at a moderate disadvantage relative to passenger cars on vertical curves and at a greater disadvantage on horizontal curves on which their higher eye height is not a help [30].

Studies by Harwood et al. [10] have found that a truck with conventional brake system driven by a poor performing driver would require 425 ft more stopping sight distance and longer vertical crest curves at 70 mph. However, a similar truck driven by a good performing driver requires only slightly more stopping sight distance and shorter crest vertical curves than AASHTO's recommendation. A truck with an anti-lock braking system has been found to require less stopping sight distance and significantly shorter crest vertical curves than the current AASHTO policy. Due to these mixed results, no change in stopping sight distance requirement is recommended.

The required stopping sight distances according to AASHTO are 400 ft at 45 mph, 550 ft at 55 mph, and 725 ft at 65 mph [1]. Improvement of sight distance can reduce a number of collision accidents, especially rear-end collisions.

5.3.1.4 *Bridge Width*

Bridge width, both absolute and relative to approach roadway has been a major factor affecting safety at bridge sites. The greater the difference between the clear bridge width, which includes the travel lanes and the usable shoulders on bridge structure, and the width of the approach lanes, the greater is the accident rate. Narrow bridges pose a greater problem for large trucks than for passenger cars. Bridge width has been considered because of the potential consequences possible due to a hazmat accident and resulting in releases over a bridge.

Ideally, the bridge width should be at least the same as approach roadway width from the safety point of view. However, the high costs associated with the construction of bridges restrict the width. The relative bridge width, i.e., the difference between the actual bridge width and the travel way width should be as large as possible. [17]

5.3.1.5 *Vertical Grade*

A number of accident studies on vertical grades have been conducted which yielded the following general relationships: [26]

1. Grade sections have higher accident rates than level sections.
2. Steep grades have higher accident rates than milder grades.
3. Down-grades have higher accident rates than up-grades.

A very high percentage of accidents involve trucks with high weight-to-horsepower ratio. This is because on steep up-grades, a loaded truck travels at lower speeds which could result in rear-end collision accidents. Wherever

possible, it is advisable to provide flatter grades. Climbing lanes should be provided in locations where the speed differential between trucks and other vehicles is greater than 10 mph. On down-grades, there is a high probability of loss of control of truck resulting in severe rollover accidents [8].

Flattening the grades has been a part of Resurfacing Reconstruction and Rehabilitation (RRR) practice. In this model, grade less than 1% is defined as the most ideal condition.

5.3.1.6 Clear Roadside Recovery

Approximately 30 percent of accidents on two-lane rural roads involve single vehicles running off the road. According to the analysis of truck accident databases, there is a high percentage of single vehicle accidents resulting in a release. The release of hazmat is usually caused due to steep side slopes, presence of fixed objects, etc.

A number of studies in the past have indicated that there is a significant relationship between roadside recovery distance and accident rates and that increasing clear recovery area would reduce both the number of accidents and severity. When there is enough clear area, the chances of safe recovery of errant vehicles are excellent. The recommended recovery area should extend outward at least 30 ft from the edge of traveled lanes and have sideslopes no steeper than 6:1.

5.3.1.7 Median/Median Barrier

The presence of median/median barrier on a highway is of crucial importance because it eliminates the possibility of head-on conflict under almost all conditions. A head-on collision accident involving a hazmat carrying vehicle can be potentially catastrophic. It is necessary to control the number of potential conflicts as far as possible. Wide medians are recommended. However, barrier rails capable of restraining hits from either ends can also be provided and should be provided on narrow medians. The width of median or type of barrier is not considered because the main focus is whether or not a median/median barrier is present.

All the above geometric elements will be considered in determining the mitigation measures. In order to collect the data, a survey form is prepared. Based on the analysis of this data, necessary improvements can be recommended.

Table 5.1 presents a summary of the geometric elements considered and the safe conditions for truck travel. Once the geometric elements have been identified, the effectiveness of the improvements have to be determined. This is described in the next section.

5.3.2 Effectiveness of Geometric Design Improvement

This section covers the process of determining the effectiveness of improvements selected by the user in terms of the reduction of risk. The part of risk which is affected by geometric improvements is the **accident probability** that is achieved by reducing truck accident rate. The data needs to accomplish this are

Table 5.1

SAFE GEOMETRIC CONDITIONS FOR TRUCK TRANSPORTATION

Geometric Design Element	Unit	Safe Condition
Lane width	ft	12
Shoulder width	ft	12
Shoulder type	Paved/Unpaved	Paved
Degree of curvature	Degree	0
Sight distance	100 ft	550 ft (55mph)
Bridge width (shoulders)	ft	10
Vertical grade	percent	1
Clear roadside recovery	ft	30
Median/Median barrier	Y/N	Yes

truck accident rate reduction factors for the improvement of the above geometric elements.

Extensive search of available literature was carried out in attempt to quantify the improvements in terms of truck accident rate reduction. However, there were two main drawbacks:

1. a majority of prior research focused on rural highways; thus urban highway features are not specifically addressed.
2. the studies were primarily concerned with passenger vehicles.

Truck accident studies have been given priority only recently and there is currently no good data available to permit statistically valid analysis. In evaluation of highway safety using accident rates as a measure, two types of data are needed. The first is accident data. The type of accident data needed varies depending on the issue. For hazmat accident analysis, data should be available on all truck accidents, categorized by truck configuration. The other relevant data needed are the time and location of accidents, type of accident, highway or segment type, factors involved etc. These accident measures are typically expressed in terms of accident rates i.e., accident per million vehicle miles of travel. The denominator of the rate expression is the exposure value which is the second principal type of data required. In establishing hazardous materials transportation policies, the ideal situation would be risk measures that could be be made very specific. An accident rate for a particular type of truck traveling on a particular type of road or road segment can be obtained only if both the accident and exposure data are stratified accordingly. Both data sets should cover a sufficiently long period of time which can be checked statistically with a Chi-squared test as previously explained in this report. However, valid exposure data corresponding to a particular truck, highway or accident type are seldom available [9, 19].

Regarding the effectiveness values of protective systems which have to be incorporated into the model to obtain risk reduction, data are not available. Obtaining truck accident reduction factors will involve extensive study of accidents before and after the improvements and will have to be developed over time in the future. The only other data which are available is the effectiveness in terms of all vehicle accident reduction factors. A TRB study [29] on the safety impact of resurfacing, restoration and rehabilitation has made possible research determining possible accident reduction potentials of various highway elements. In a study conducted by Sinha and Hu [26], 14 major highway design elements that have significant effect on safety, were selected. For these elements, the improvement was measured by a unit measure. For example, the unit of lane width is 1 foot, while the improvement of sight distance was measured by 100 ft. Then the relationship between these individual highway design elements and accident reduction rate was derived using the literature available in the NCHRP project 3-25 [20]. The quantified highway accident reduction rate values described in the NCHRP report were related to specific highway class and design element. The existing data included four different highway types: interstate, four-lane undivided highway, two-lane rural highway and urban arterial. The accident reduction rates related to the highway design elements were evaluated under each class of highway.

It was decided that these factors can be used at present as default values. This can be easily imbedded in the risk model. Moreover, all the effectiveness values are in terms of a common unit - number of accidents reduced per million vehicle miles. Some of these values are used in the program. The effectiveness values for bridge width and clear roadside recovery are obtained from studies by Mak [17] and the TRB report [29] respectively. These are listed in Table 5.2. The type of accident

correlated with geometry elements is presented in Table 5.3. Appendix C has a more detailed listing of the accident type and the related geometric design elements.

However, it should be made clear that these effectiveness are for all vehicle accidents and have to be substituted by some reliable truck accident rate reduction factors when available.

5.3.2.1 *Combining Different Improvements*

The accident effects for situations in which two or more highway features are improved simultaneously is difficult to estimate. Interactive effects of such combined treatments have not been modeled. In the absence of such models, ad-hoc procedures are required to estimate the accident reduction likely to result from two or more simultaneous improvements.

A first order approximation of combined effects, in use for many years is illustrated for three simultaneous improvements as follows:

$$ARF_c / 100 = 1 - (1 - ARF1 / 100)\ (1 - ARF2 / 100)\ (1 - ARF3 / 100) \qquad (5.1)$$

Where ARF_c is the accident reduction factor, expressed as a percentage, expected from the combination of improvements; and ARF1, ARF2 and ARF3 are similar factors representing the effects of the first, second and third improvements, respectively. However, it should be noted that it does not account for the interaction among the combined improvements [29].

In the model, once the improvements are selected, the total accident reduction is obtained and the percentage reduction factor for each design element improvement is computed. Using the above formula, the combined effectiveness of

Table 5.2

EFFECTIVENESS OF HIGHWAY IMPROVEMENTS

		Number of Accidents Reduced per Million Vehicle Miles			
Element	Unit	Interstate	Four-lane Undivided Highway	Two-Lane Rural Highway	Urban Arterial
Lane width	ft	N/A	0.275	0.260	--
Shoulder width	ft	N/A	--	0.230	0.230
Shoulder type	paved/unpaved	0.246	0.246	0.310	0.310
Degree of curve	degree	0.340	0.220	0.330	0.390
Sight distance	100 ft	0.001	0.012	0.092	0.092
Bridge width	ft	0.04	0.04	0.04	0.04
Vertical grade	%	0.750	0.750	0.200	0.250
Clear roadside recovery	ft	0.03	0.03	0.03	0.03
Median/Median barrier	Yes/No	-	0.012	0.012	-

Source: Mak [17], NCHRP [20], Sinha & Hu [26], TRB Report [29]

Table 5.3

HIGHWAY ELEMENTS TIED TO ACCIDENT TYPE

Design element	Run-off road	Overturn	Head-on	Rear-end	Side-swipe
Lane width	X		X		X
Shoulder width	X		X		
Shoulder type	X	X			
Degree of curvature		X		X	
Sight distance	X			X	
Bridge width	X		X		X
Clear roadside recovery	X	X			
Median/Median barrier			X		

Source: Transportation Research Board, "Designing Safer Roads". Special Report 214, 1987

all the improvements considered is obtained. This is used to obtain the reduced risk value.

5.4 Consequence Reduction

This is the second stage of mitigation of risk. The intent is to reduce potential consequences due to the release of hazmat on highways by developing protective systems for various scenarios. This is an extension of an earlier work done by Russell "Protective Systems for Spills of Hazardous Materials: Volume I Final Report and Volume II Guidelines" [23,24].

It was found that the concept of designing protective measures into highway systems specifically to prevent or mitigate hazardous materials spills was new and unique. No U.S. literature existed that directly addressed this concept. Literature on systems that could be adapted to the concept, such as drainage containment systems, high strength barrier rail, etc., was available. However, 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. This research focused on potential risks which would result in severe, long-term, permanent, irreparable or catastrophic consequences and existing technology and state-of-the-art knowledge for the development of selected protective systems. The material presented in these reports should provide a framework to guide the state to a decision on the practicality of designing a specific system.

5.4.1 Development of Scenarios and Protective systems

5.4.1.1 Development of Scenarios

The design and implementation of a physical protective system on a route or route segment is costly and probably only justifiable in high risk areas or areas where there is catastrophic potential. The first task is to define the catastrophic nature of spills. In order to aid in the development of generalized scenarios, Russell [23] used an advisory panel of contacts from 27 interested states. This approach reflected true concerns of states in regard to potentially catastrophic situations that could occur during the transport of hazmat on highway systems. The advisory panel was asked for real or hypothetical scenarios that they felt were of concern to their state. Approximately 60 separate, independent scenarios were suggested. Through several rounds of rankings, the original 60 scenarios were narrowed down to 11. Most fell into a few categories such that by generalizing a statement covering the category, several of the original scenarios fit each statement. Thus, the process of narrowing down the scenarios was more a process of fitting all 60 into 11 general statements rather than picking the top 11 and discarding 49. These were then compared with the situations in Pennsylvania, and 9 of the eleven scenarios were found to be applicable. These are listed in Table 5.4. Although these are believed to fit Pennsylvania, they are still general. However, they can easily be made site-specific as needed by planner/designer.

This set of scenarios is sufficiently comprehensive and general enough to use in seeking a set of corresponding protective systems to be incorporated into new or reconstructed highway segments. The intent in developing these scenarios is to

Table 5.4

GENERAL - POTENTIALLY EXTREME RISK SITUATIONS IN PENNSYLVANIA

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.

2) Chemical spills of poisonous or explosive materials that could enter background **"METRO" stations or transit tunnels** through side-walk 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 there-to, 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) Releases from accidents between hazardous materials containers on highways and passenger trains or trains causing 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**.

7) Explosive materials in facilities in populated areas 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 related 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 material carriers could cause catastrophic consequences to the populated areas.

emphasize the need for a state to be on the alert for possible high-risk scenarios that should be analyzed by recommended risk procedures to determine if protective systems should be considered. The result should be a state check list of highway sections to be considered for risk analysis and possible protective systems. It should be noted that the scenarios may have to be modified based on site-specific needs. This report would form a basis for such developments. The types of protective measures recommended to be considered will be listed in the next section.

During the survey by Russell to the panel to determine the catastrophic scenarios, 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. One easy way to summarize this survey result is that all releases are going to go down, up, or laterally, and the panel rated their catastrophic potential in that order.

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, in that order.

The study showed no significant difference between materials, indicating, for the materials given, the location of the incident was generally perceived as being more important than the material. Chlorine was an exception; i.e., the respondents perceived Chlorine to be significantly more dangerous than other materials considered in this study. Table 5.5 shows how the responders ranked the receptor facilities adjacent to highways.

Table 5.5

GENERALIZED HIGHWAY FACILTIES OF HIGH RISK

Elevated facilities with development below

Depressed facilities with development over

Any facility adjacent to vulnerable population in order of:

a) nursing homes or hospital
b) schools
c) apartments
d) shopping center
e) hotel
f) factory
g) hazmat storage facillities

Drainage into sewage system

5.4.1.2 *Development of Protective Systems*

After developing the generalized scenarios, the next task was to develop "feasible, implementable, and practical" protective systems keyed to the scenarios. Deciding on what were feasible, implementable, and practical protective systems proved to be very difficult. Given unlimited resources and modern technology, any system is feasible and implementable. However, states do not have unlimited resources. Thus the practical aspect of the protective systems was the key criterion. This can be decided only by the state decision makers themselves by taking into account the cost-benefit of the protective system within the context of overall state priorities and resources. Ideally, benefit should be measured in terms of risk reduction, but this is difficult at present because the data necessary to do a meaningful risk reduction analysis on untried protective system concepts is not possible nor will be until there is a history of performance of a particular protective system.

Currently, there are only a few protective systems that appear to have clear cut merit in reducing risk of hazmat spills and/or mitigating consequences in specific situations. The most promising and the most applicable, to many high-risk situations are in two general categories:

1. High-strength rail to keep hazmat vehicles within the highway segment 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 a considerable effort.

Here the states' advisory panel, formed for the purpose of scenario development and ranking was again utilized. The original protective system ideas came from this panel, and, after these were stored and organized, the panel was surveyed for protective system ideas. Ninety eight were generated. The panel was asked to rate these protective systems on a scale of 1 to 7. The key to the 1-7 rating scale is presented in Table 5.6. In general terms, where all protective systems 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. The ninety eight protective system ideas were cut down to thirty-two responses which were analyzed and the mean, standard deviation, maximum and minimum scores of each protective system were calculated. These are listed in Table 5.7. The results of protective systems keyed to generalized scenarios is presented in Table 5.8.

Protective system ideas were then evaluated by the panel in terms of percentage reduction of risk. This ensured that the estimates should not be too far outside of what an individual state decision-maker would consider reasonable in a rough estimate of its cost-effectiveness. Design details of these protective systems are left to the state and/or manufacturers, suppliers and consultants with expertise in various specific areas. Some are readily applicable; others obviously would require further study to implement.

Communication and automatic detection systems were mentioned in the responses to almost all scenarios. These systems are an example of systems received to have great value but need further research and development to be adapted to highways.

Based on the responses of the panel, regulatory type preventive measures dominated suggested solutions. Conversely, it can be concluded that the physical,

Table 5.6

SCALE TO RATE PROTECTIVE SYSTEMS

Scale	Value	Key Guidelines to Assist Raters
Bad (Worst)	1	Nearly impossible to implement, not at all practical, will serve no useful purpose
	2	Very diffucult 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, i.e., excellent and very desirable

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 approach system is clearly effective, and the risk is deemed high enough to offset the cost. This is a policy decision, and is the heart of the practicability criterion mentioned previously.

All others can be classified as physical protective systems, which includes preventative (accident reduction measures) and mitigating (consequence reduction measures). The latter dominate 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.

5.4.2 Effectiveness of Protective Systems

The protective system ideas obtained through the panel of various states' personnel is a new concept in hazardous materials research. Most of these systems have never been implemented in highway situations and thus the effectiveness of these are not known. It was decided that the best alternative is to provide approximate values for the effectiveness until better values are obtained which could be done by the panel. Option is provided to the user to input his/her own values of effectiveness. The panel should be a reasonable first estimate.

Questionnaires were again mailed to the panel members to provide estimates about potential consequence reduction and also rate their answers on a scale of 1 to 10, where, 1 would mean strictly a guess and 10 being the case when the person is sure of the answer. This was carried out in stages. Physical protective system ideas

Table 5.7

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 Crossovers
B. Systems to facilitate escape and Response	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. Systems 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 using 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. Preventive
A. Containment	High performance barrier systems
B. Control	Truck escape ramps Upgrade truck runoffs Wide shoulders

Table 5.8

PROTECTIVE SYSTEMS KEYED TO SCENARIOS

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

Rank		% Reduction
1	Traversable medians	50
2	Emergency phone call boxes on all hazardous cargo routes	25
3	Crossovers	30
3	Median openings	30
4	Highway exits designed for traffic entrance (response team) from opposite direction	30

Regulatory measures

1	Routing restrictions	65
2	Prohibition on hours (curfews)	45
3	Prohibit large trucks through congested areas (routing)	55

Scenario 2: Chemical spills of poisonous or explosive materials that could enter background "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

Rank		% Reduction
1	Fresh air vents at elevated levels	50
2	Prohibition in areas; air vents intakes away from the roads, arrows in tunnels with distance to exit, etc.	50
3	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	45
5	Pea-trap system vents to trap gases in first section	40

Regulatory measures

1	Restricted routing in these areas	70

Table 5.8 (Contd..)

Scenario 3: Hazardous materials accidents causing release of toxic, flammable or explosive materials in tunnels.

Protective systems

Rank		% Reduction
1	Arrows pointing to nearest exit	30
2	Effective vent systems	45
3	Monitoring for quick response	50
4	Gas detectors/alarm systems	35
5	Large sprinkler systems	30
6	Emergency exits with heavy doors	25

Regulatory measures

1	Routing hazmats away from tunnels	80

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

Rank		% Reduction
1	High performance barrier/rail systems to prevent such an accident	60
2	Avoid use of open rails on structure	45
3	Robust drainage with holding reservoirs that can be isolated from regular storm drains (and later pumped) should a spill occur	40
4	Conduit railing for automatic spraying of water	25
4	Relocate or close ramps--in critical locations; install improved barriers; prohibit truck use of such ramps	60

Regulatory measures

1	Reduced speed	40
2	No hazmat through high urban area (prohibition)	75

Table 5.8 (Contd..)

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

Rank		% Reduction
1	Communication and Detection systems	50
2	Development of a public notification system for efficient evacuation possibly using air raid type alarms and public address systems	50

Regulatory measures

1	Evacuation planning	50
2	Emergency response training	50
3	Reduced speed with strict enforcement	45
4	Routing/prohibition	75
5	Training of personnel of schools, hospitals, hotels, nursing homes	50

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

Rank		% Reduction
1	Installing effective barriers between parallel transport corridors	60
2	Shared rights-of-way should be separated by concrete barriers	60
3	Higher, stronger, etc., barriers next to transit	65

Regulatory measures

1	Specific training for fire department, police etc.	45
2	State-of-art crossing warning systems	50
3	Sufficient warning indicators installed reasonably well in advance of crossings	40
4	Restricting hazmat transportation routes to avoid high hazard areas	65
5	Law requiring full stop before crossing	40

Table 5.8 (Contd..)

Scenario 7: Explosive materials in facilities in populated areas 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.

Protective systems

Rank		% Reduction
1	Communication and Delection systems	50

Regulatory measures

1	Increase inspections	45
2	Insure inspection and regulation of storage facilities	50
3	Escort vehicle for explosives	35
4	Control speed	40
5	Mandate restrictive zoning prohibiting certain chemical storage/processing around certain traffic/population density situations	60
6	Zoning restrictions to avoid popultion build ups in such areas, i.e., cognizant of the raw materials and products that will be kept in storage	60
7	Routing/prohibition	65
8	Thermal protective coverings on packages	40

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

Rank		% Reduction
1	Drainage gutters to direct spilled material toward collection point	60
2	Design with clay blanket or barrier membrane; direct drainage away from sensitive areas	60
3	Floating surface barrier (for insoluble petroleum oils)	45
4	Robust drainage with holding reserviors that can be isolated from regular storm drains should spill occur	55
5	Large sumps	50
5	Retention basins that can automatically close to capture spillage	55
6	Grease trap sedimentation basin (for heavier insolubles)	40

Table 5.8 (Contd..)

Scenario 8 (Contd..):

Regulatory measures

1	Insure inspection and regulation of storage facilities	50

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

Rank		% Reduction
1	Truck escape ramp	70
2	Upgrade runoffs for deceleration and extra wide shoulders	60
3	Construct massive barrier and put energy absorbing material in front	30

were sent out first. The results obtained were complied and sent back to the panel for their consensus along with the regulatory protective system ideas. The questionnaires used and the summary of results at various stages have been attached to this report (Appendix A). Table 5.8 shows the summary of results of the survey. As emphasized previously in this report, this is a very recent concept and hence there is no verifiable data to compare with their results. However, this provides a starting point that we conclude is reasonable and valid for making initial decisions about effectiveness of the protective systems.

5.5 *Mitigation Design Methodology*

In the previous sections, the concept of mitigation is introduced and a number of measures which can be considered to mitigate the risk due to the transportation of hazardous materials is presented. In this section, a decision making methodology of deciding on the protective systems is presented.

Mitigation measures are applied to highway segments and high risk locations/scenarios on highways. Mitigation follows risk assessment for specific route or section. Using the recommended risk model procedure, the risks on various highway segments for a municipality or county are determined. These segments are ranked based on the level of risk. Then the user can select the segments with high risk and consider them for mitigation purposes. Note that the user must decide what level of risk is high enough to warrant attention. It is recommended that default values be used for risk assessment and mitigation when statistically significant data on accidents is not available. Mitigation can also be used in routing. The user may

consider improvements on some specific, high-risk segments so that they become minimum risk or low risk routes after the improvements.

Consider a high risk street segment requiring mitigation. This risk is made up of two components: probability and consequence. Probability is based on the truck accident rate and consequence is based on the exposure to population, property, environment etc. Based on the value of probability and consequence, the following scenarios arise:

- high probability, high consequence
- high probability, low consequence
- low probability, high consequence.

The mitigation measures can be considered accordingly. However, it is recommended that both probability and consequence reduction measures be considered for the segment under consideration since hazardous material incidents are very rare events and one cannot rely completely on historical data on the probability of an incident and the resulting consequences i.e., one cannot say the risk is zero on a segment that has never had a recorded accident. This is a case where default values or state averages should be used.

The first step is to make a survey of the segment. A field check form is provided, which can be used to obtain or check the data on the existing geometric conditions and high hazard scenarios. One should also be certain that the segment meets all the minimum requirements of geometry as specified by the AASHTO [1]. The geometric design check is done to make sure that the segment is generally safe for the movement of trucks, whereas the high hazard scenarios are checked for specific potential consequences.

The data obtained by the field form has to be compared with the safe conditions for truck travel and necessary improvements can be considered. The user can

simulate improving all or some of the elements from their present condition to the recommended safe condition. It is recommended that the accident data be reviewed carefully to determine if any particular type of accidents occur frequently and consider accident specific measures to reduce them. This can be done with the help of Table 5.3. The effectiveness of these improvements are listed in Table 5.2.

Once the user selects the improvements and the effectiveness values, the probability reduction due to potential reduction of truck accident rate can be calculated.

Then the consequence reduction measures can be considered. It is necessary that the user obtains detailed maps of the area under consideration at this stage. The street segment and the surrounding area within the impact width of hazardous material has to be considered in consequence reduction measures. All high risk locations have to be identified and considered according to their relative importance. This can be accomplished by checking for high hazard scenarios within the impact area. A roadway segment can have any number of these scenarios. For each of these, possible mitigation measures are available along with estimated effectiveness factors. Based on these values the consequence reduction value is obtained.

The combined effect is the reduction of risk on the highway segment.

6.0 APPLICATION OF MODEL

Case studies were conducted on some highway segments in order to get a first hand experience on the applicability of the model. The highway segments were selected based on the value of risk. The accident data on all the segments were obtained from the Accident Record System file supplied by the Pennsylvania DOT. The consequence data at municipality level was provided under contract by Keystone Management Systems, Inc. These data were used to get values of risk for various highway segments. It is to be noted that this is not the actual value, since average consequence was used. On analysis, it was found that Philadelphia has the maximum number of segments with high risk. About 50% of the top 100 high risk segments of Pennsylvania are in Philadelphia.

Six segments on Interstate 76 and a segment on Route 3019 in Philadelphia were selected for this case study. The main purpose was to make a survey of the segment and obtain the data necessary to do detailed risk assessment and mitigation. For risk assessment, the data on population, property, etc. along the highway segment is required, whereas for mitigation, the possible causes of accidents, highway geometry and potential catastrophic scenarios along the highway segment are to be used. Two segments were analyzed and the results are presented in this report.

Population data was obtained from the census tract maps. The data on property and special facilities were not available. Thus, only population risk is considered. Figure 6.1 shows the census tract map of Philadelphia with the segments marked.

The other data collected are shown in Tables 6.1 and 6.2. The geometry details of the segments are presented in in Figures 6.2 and 6.3. Aerial photographs of the segments have been obtained in order to get an understanding of the scenario. This are shown in Figures 6.4 and 6.5.

6.1 Population Risk

As already mentioned risk is the product of probability and consequence. The probability of hazardous material truck accident depends on the number of hazmat accidents. However, this is a small number at segment level. The maximum number of hazardous material accidents on any segment in Pennsylvania in the past five years is 4. Moreover, there is no exposure data, i.e., volume of hazmat trucks is not known. Hence, all truck accidents was used instead.

Consider the Segment 3431 on Interstate 76. The first step in risk analysis is to find out whether the observed accident data is statistically significant. The number of truck accidents observed over the past five years is 24. The expected truck accident rate on urban freeway as suggested by MRI [11] is 2.18 accidents per million vehicle miles. The Chi-square test mentioned earlier can be carried out:

The expected number of truck accidents is

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

Where

TAR = 2.18 accidents per million vehicle mile

TADT = ADT truck = 7116

Table 6.1

DATA ON SEGMENT 3420

County - Philadelphia	Municipality - Philadelphia
State Route No - I-76	Segment - 3420
Highway type - Interstate	Area type - Urban

Accident Data

Number of Truck Accidents	14
Predominant Accident Type(s)	Rear-end Angle

Geometry Data

Lane width	3-12 ft lanes
Shoulder width	4-8 ft right shoulder
Shoulder type	Paved
Degree of curvature	Sharp compound curve
Sight distance	Restricted
Vertical grade	Slight downgrade (-2%)
Bridge width	2 ft less shoulder at bridge
Clear roadside recovery	None
Median/Median barrier	Yes

Type of Scenario	1

Comments

Very high possibility of accidents on curve
Presence of high volume of traffic

Other Data

ADT Truck	7116
Segment Length	0.5 mi
Population within 0.5 mi	45126

Table 6.2

DATA ON SEGMENT 3431

County - Philadelphia	Municipality - Philadelphia
State Route No - I-76	Segment - 3431
Highway type - Interstate	Area type - Urban

Accident Data

Number of Truck Accidents	24
Predominant Accident Type(s)	Rear-end Angle, Side-swipe

Geometry Data

Lane width	3-12 ft lanes
Shoulder width	0-4 ft right shoulder
Shoulder type	Paved
Degree of curvature	compound curve
Sight distance	Restricted
Vertical grade	None
Bridge width	N/A
Clear roadside recovery	None
Median/Median barrier	Yes

Type of Scenario	1, 8

Comments

Less acceleration and deceleration lane lengths at ramps.
Very high possibility of accidents on curve.

Other Data

ADT Truck	7116
Segment Length	0.5 mi
Population within 0.5 mi	100479

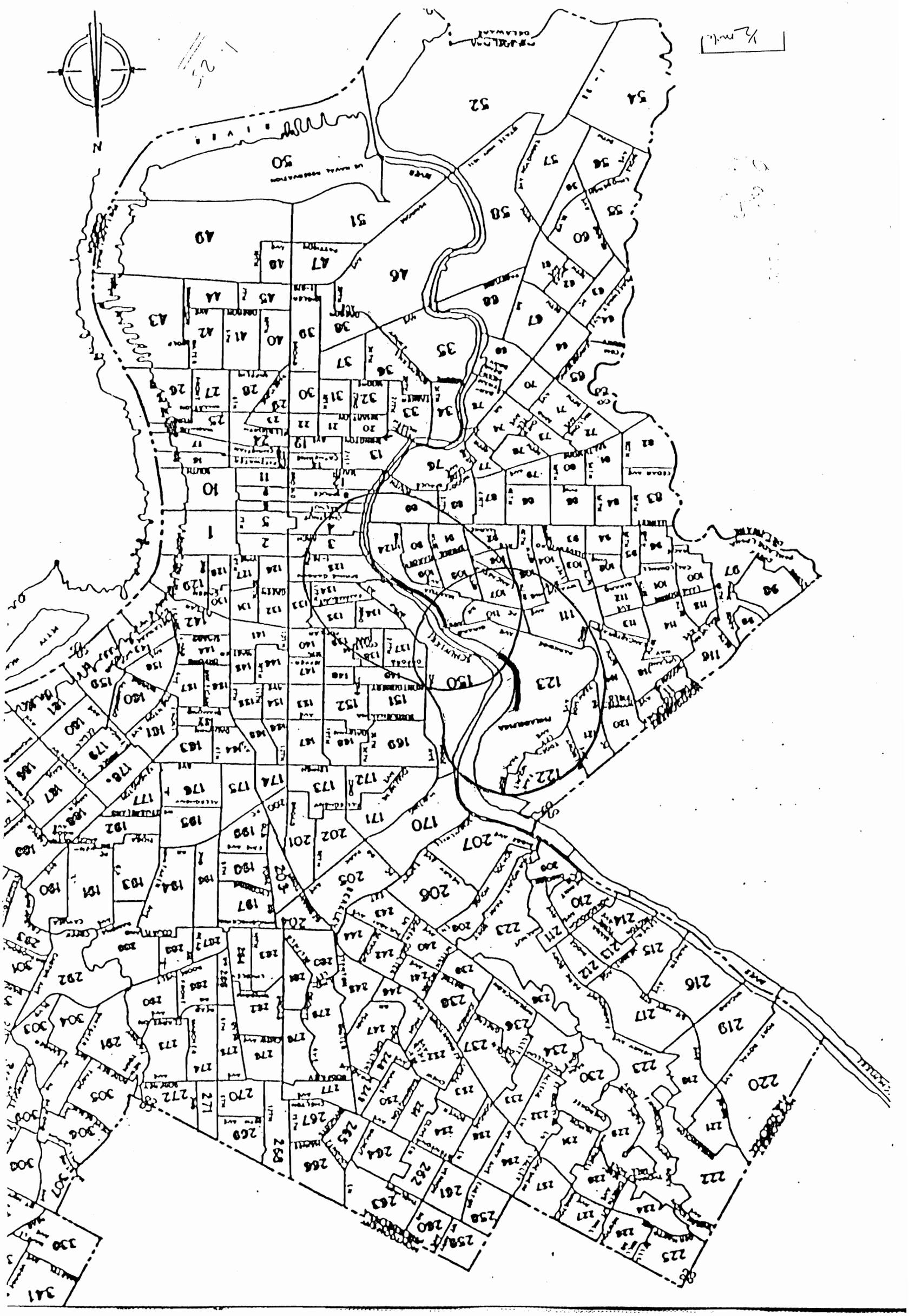
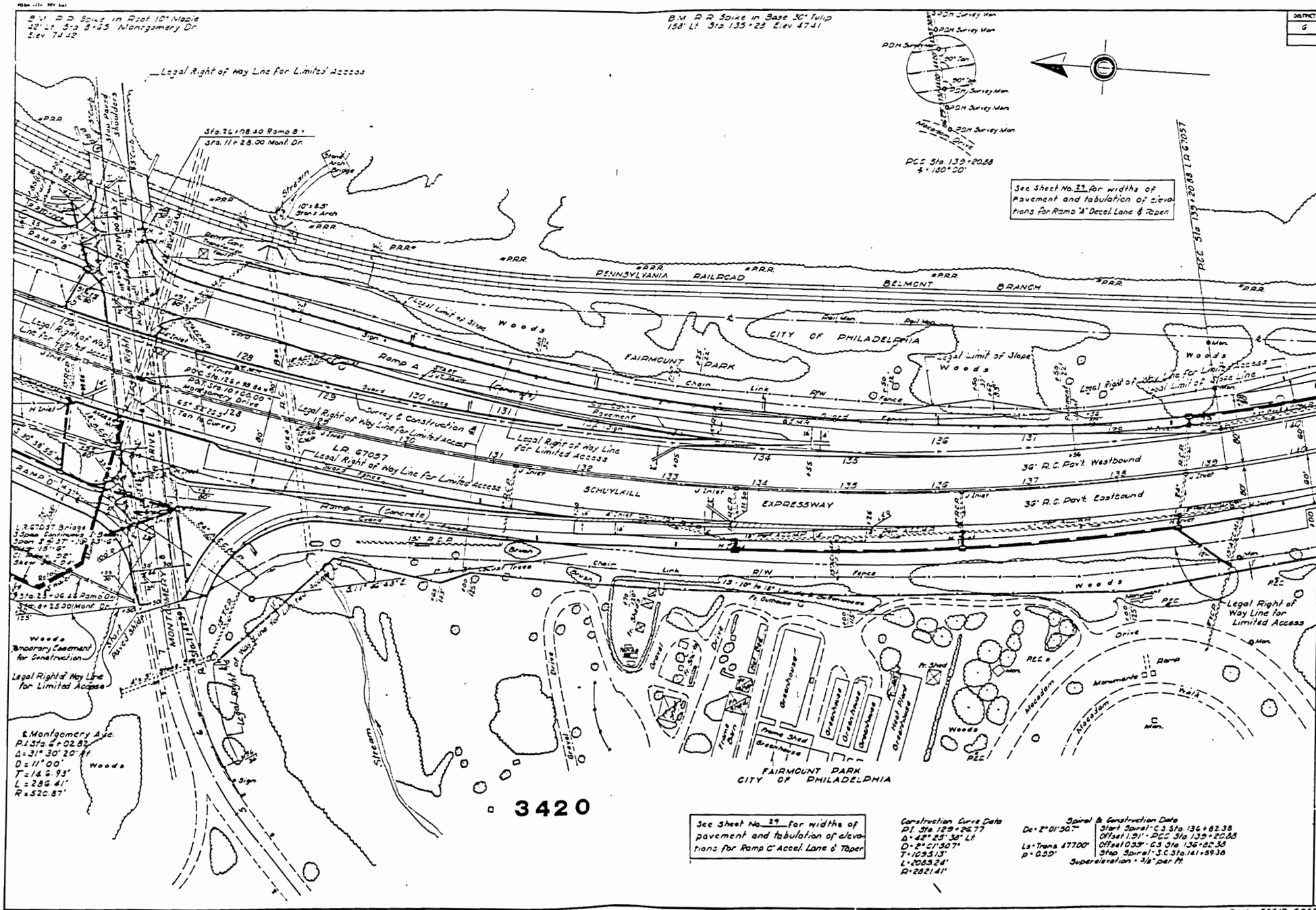


Figure 6.1. Census Tract Map of Area Around Segments 3420 & 3431

DISTRICT	COUNTY	ROUTE	SECTION	SHEET
6	PHILADELPHIA	67057	13	17 of 37
CITY OF PHILADELPHIA				



Line Book - 50617 - 50623, 50619
B.M. Book - 50618

REQUIRED LIST

FOR REQUIRED LIST SEE SHEET No. 17A OF 37 COLUMN Nos. 4, 5, & 6

Sta. 127+50 to Sta. 133+00
449 C.Y. Cl. 1 Exc. (Paved Shldrs. Lt.)
25 C.Y. Emb.

Sta. 127+00 to Sta. 132+00
233 S.Y. Topsoil Furnished and placed (4" depth Rt.)

Sta. 127+80 to Sta. 132+00 (Rt.)
137 C.Y. Cl. 1 Exc. (Paved Shldrs. Rt.)
20 C.Y. Emb.

Sta. 128+55 (Ramp C Rt.)
16 L.F. 12" A.C.C.M. Pipe
1 Ea. Slope Pipe Fitting For 12" A.C.C.M. Pipe, Type A
3 C.Y. Cl. 2 Exc. (Pipe) Cl. C Bedding

Sta. 128+75 to Sta. 130+25
137 C.Y. Cl. 1 Exc. (Bench for Emb., Rt.)
137 C.Y. Emb. (Bk. Fill)

Sta. 130+60 (Lt.)
12 L.F. 12" A.C.C.M. Pipe
1 Ea. Slope Pipe Fitting For 12" A.C.C.M. Pipe, Type A
2 C.Y. Cl. 2 Exc. (Pipe) Cl. C Bedding

Sta. 129+75 to Sta. 131+25
259 C.Y. Cl. 1 Exc. (Bench for Emb. Lt.)
259 C.Y. Emb. (Bk. Fill)

Sta. 129+84 (Ramp A Lt.)
24 L.F. 12" A.C.C.M. Pipe
1 Ea. Slope Pipe Fitting For 12" A.C.C.M. Pipe, Type A
5 C.Y. Cl. 2 Exc. (Pipe) Cl. C Bedding

Sta. 131+24 to Sta. 131+90 (Ramp C Lt.)
1 C.Y. Fine Aggr. For Extra depth U/drain
2 C.Y. Cl. 2 Exc. (Extra depth U/drain)

Sta. 132+00 to Sta. 135+24
324 L.F. Conc. Tr. Sep. - B (Rt.)

Sta. 132+04 (Ramp A Lt.)
12 L.F. 12" A.C.C.M. Pipe
1 Ea. Slope Pipe Fitting For 12" A.C.C.M. Pipe, Type A
2 C.Y. Cl. 2 Exc. (Pipe) Cl. C Bedding

Sta. 132+73 to Sta. 133+75 (Rt.)
34 C.Y. Cl. 2 Exc. (Remove Exist. Pipe & Inlet)

Sta. 132+75 to Sta. 133+25
43 C.Y. Cl. 1 Exc. (Bench for Emb. Lt.)
43 C.Y. Emb. (Bk. Fill)

Sta. 133+50 (Lt.)
0.1 C.Y. Cl. B Conc. (Plug Exist. Pipe)
13 C.Y. Cl. 2 Exc. (Remove Exist. Inlet & Pipe under shoulders)

Sta. 133+78 (Rt.)
8 L.F. 15" R.C.C. Pipe Cl. III (Connect to Exist. Pipe)
1 Type H Inlet, Revised, using Exist. Castings
2 C.Y. Granular Mat'l.
8 C.Y. Cl. 2 Exc. (Remove Exist. Inlet)
4 C.Y. Cl. 2 Exc. (Pipe) Cl. C Bedding

Sta. 133+78 to Sta. 136+25 (Rt.)
92 C.Y. Cl. 2 Exc. (Remove Exist. Pipe)

Sta. 133+78 to Sta. 138+20 (Rt.)
474 L.F. 18" Ex. Str. Pl. C.C. Pipe or Ex. Str. V.C. Pipe or C.M. Pipe
316 C.Y. Cl. 2 Exc. (Pipe) Cl. C Bedding

Sta. 134+00 (Lt.)
6 L.F. 12" A.C.C.M. Pipe
1 Ea. Slope Pipe Fitting For 12" A.C.C.M. Pipe, Type A
1 C.Y. Cl. 2 Exc. (Pipe) Cl. C Bedding

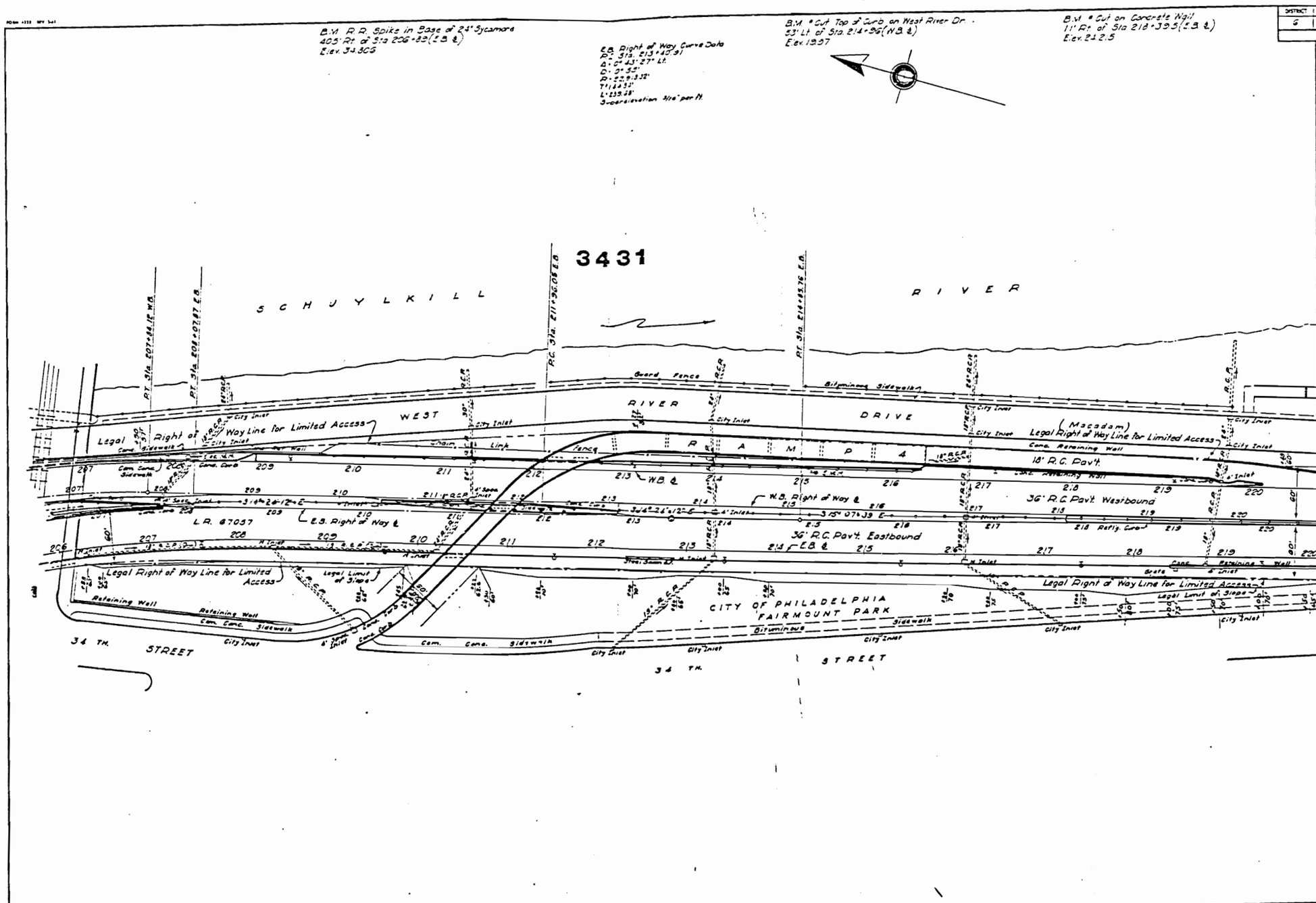
Sta. 134+88 (Rt.)
7 C.Y. Cl. 2 Exc. (Remove Exist. Inlet)

Required List Cont'd on sheet No. 30

TRACED BY J.E.S. J.K.

Figure 6.2. Details of Segment 3420

DISTRICT	COUNTY	ROUTE	SECTION	SHEET
6	PHILADELPHIA	67057	13	22 of 37
CITY OF PHILADELPHIA				



Line, Profile & B.M. Book - 50621-50622

COLUMN No. 6

FOR REQUIRED LIST SEE SHEET No. 22A OF 37

REQUIRED LIST

EASTBOUND

- Sta. 207+10 (Median)
  4 L.F. 18" R.C.C. Pipe, Cl. III
  1 Type "A" Inlet
  1 C.Y. Granular Mat'l.
- Sta. 208+45 (Rt.)
  1 set Reset Inlet Castings
- Sta. 210+00 to Sta. 220+00
  485 C.Y. Exc. (Paved Shldrs.)
- Sta. 210+23 (Rt.)
  1 set Reset Inlet Castings
- Sta. 213+30 (Rt.)
  1 set Reset Inlet Castings
- Sta. 216+13 (Rt.)
  1 set Reset Inlet Castings
- Sta. 218+39 to Sta. 219+70 (Rt.)
  50 L.F. Subgrade Drains
- Sta. 218+78 (Rt.)
  1 set Reset Inlet Castings

WESTBOUND

- Sta. 210+00 to Sta. 220+00
  641 C.Y. Cl. I Exc. (Paved Shldrs.)
  39 C.Y. Emb.
- Sta. 211+29 (Lt.)
  18 L.F. 12" A.C.C.M. Pipe
  1 Ea. Slope Pipe Fitting For 12" A.C.C.M. Pipe, Type A
  4 C.Y. Cl. 2 Exc. (Pipe) Cl. C Bedding
- Sta. 213+97 (Lt.)
  13 L.F. 12" A.C.C.M. Pipe
  1 Ea. Slope Pipe Fittings For 12" A.C.C.M. Pipe Type A
  4 C.Y. Cl. 2 Exc. (Pipe) Cl. C Bedding
- Sta. 216+37 to Sta. 219+10 (Lt.)
  190 L.F. Subgrade Drains

PLACED BY J.E.S.

Figure 6.3. Details of Segment 3431

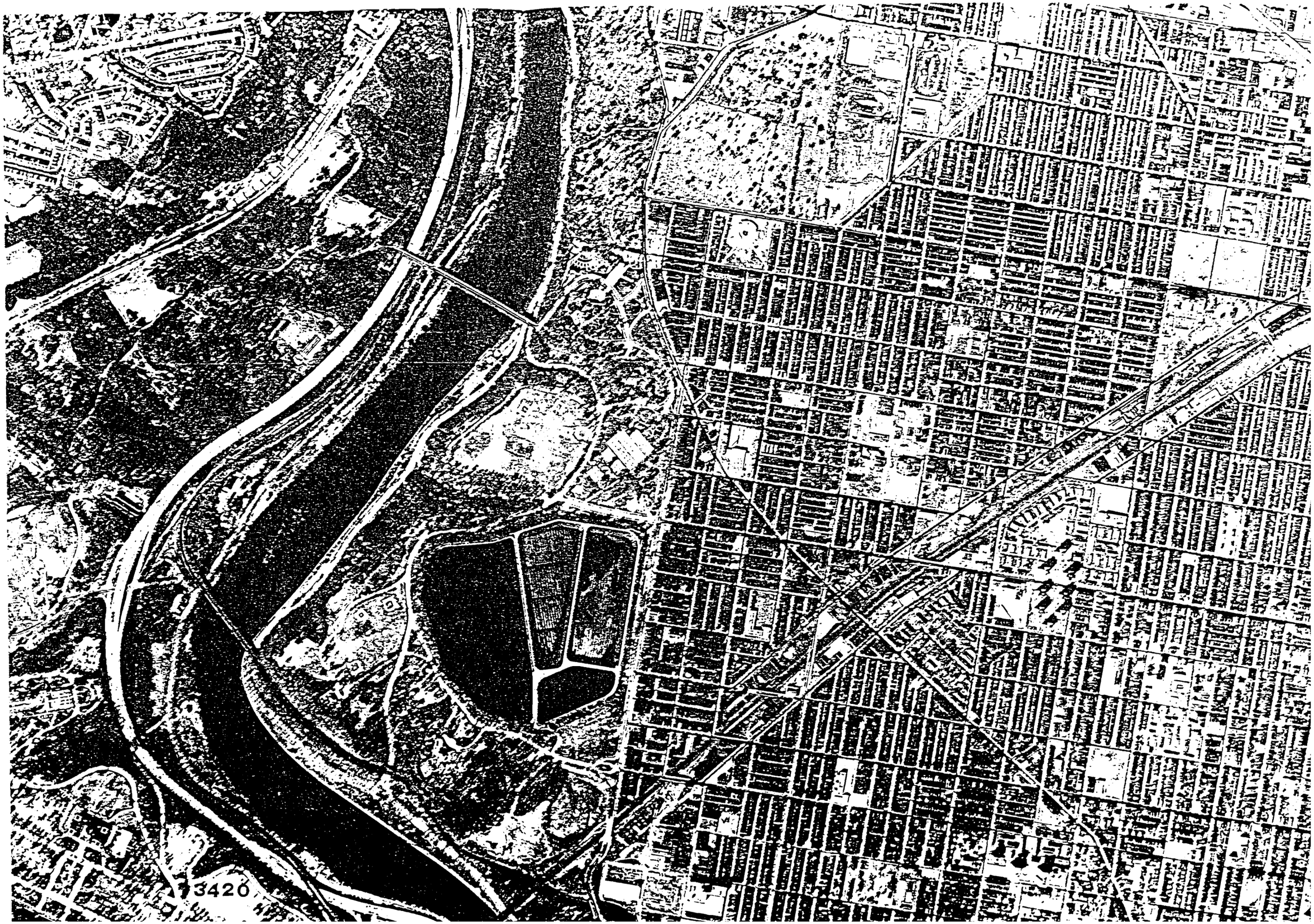

3426

Figure 6.4. Aerial Photograph of Area Around Segment 3420

3437

Figure 6.5. Aerial Photograph of Area Around Segment 3431

L = Segment length = 0.5 mile

N = Number of years = 5

Substituting the above values in the equation, the expected number of accidents is 14.16. The observed number of accidents A_o is 24. The Chi-squared statistic can be calculated as:

$$X^2 = \frac{(A_e - A_o)^2}{A_e}$$

The value of chi-squared statistic is 6.84. Since the value is greater than 4, the expected and observed number of accidents differ significantly. Thus site-specific accident data can be used as it is greater.

Now in order to calculate risk, we use the probability of all truck accidents and multiply by the probability of release using the default values at national level provided by Midwest Research Institute [11]. The first step is the calculation of TAR.

$$TAR = \frac{A_o}{TADT \times 365 \times N \times Segmentlength}$$

The value of TAR is 3.696×10^{-6}. The next step is calculation of the probability of release followed by the consequences. The probability of release based on default values as given by the MRI. This is 0.062 for urban freeway. In order to determine consequences, the actual population within the impact area has been obtained. This is obtained from census tract maps. The population within 0.5 mile of the segment is 100479. The risk is calculated as:

$$Risk = \frac{TAR \times \text{Prob. of release} \times Seg.length \times Pop.}{Seg.length}$$

The value of risk on segment 3431 has been obtained as 4.605×10^{-2}. Following a similar procedure the value of risk on segment 3420 is calculated as 6.032×10^{-3}.

6.2 *Mitigation Measures*

As mentioned earlier, the number of accidents and the distribution of accidents by type would give an indication of the potential problems on the segment. Segments 3420 and 3431 have predominantly rear-end and angle collision accidents. The reason could be reduced sight distance and less weaving areas. It has been found that the segment 3420 is on a curve and has problems of reduced sight distance. Moreover, segments 3420 and 3431 have entrance and exit ramps with inadequate merging area. These could be the reasons for rear-end and angle collisions. According to AASHTO, there should be a minimum of 900 ft of acceleration lane followed by a 300 ft tapering section to facilitate acceleration of vehicles entering a freeway with average speed of 47 mph from a ramp with an average speed of 26 mph. Similarly there should be a 250 ft tapering section followed by about 300 ft straight section for deceleration lane at an exit ramp.

Based on the above specifications, the following measures are recommended:

- Design of ramps with longer acceleration and deceleration lanes.
- Redesign of section to reduce curvature.
- Ramp control to facilitate smooth merging.
- Prohibition of hazmat travel during peak hours.
- Reduced speed limit so that it is easier to negotiate the curve.

The above measures are arrived at based on the accident data for the past five years. It is recommended that the regulatory measures such as reducing speed and imposing time restrictions be considered, at present, to the extent they are practical. The physical measures can be considered if the accident trend does not change after the implementation of these regulatory measures.

The highway segment 3420 and 3431 have been found to have a very high concentration of vehicles and so the scenario 1 (Table 5.4) is applicable. Suitable measures which can be implemented are:

Protective Systems

- Traversable medians
- Emergency call boxes
- Crossovers
- Median openings
- Highway exit designed for traffic (response team) entrance from opposite direction

Regulatory Measures

- Routing restrictions
- Prohibition on hours (curfews)
- Prohibition of large hazmat trucks through congested areas

Some of the protective systems above are to be employed to facilitate quick response. However, the response in Philadelphia is reasonable. It has been found through conversation with the Philadelphia fire department that they usually respond within five minutes. Hence, the measures recommended for consequence reduction are:

- Median openings
- Highway exit designed for traffic entrance from opposite direction.

Of the regulatory measures, prohibition on hours (curfews) has already been recommended as part of strategy to reduce accidents. Other measures such as prohibition of hazmat truck travel are not necessary at this time. It can be considered if the above mentioned measures are ineffective in reducing the risk. According to the results from the survey the expected reduction of risk by prohibition on hours of travel of hazmat truck travel is 45% and by reducing speed is 40%.

The segment 3431 is very close to the Schuylkill river and hence in addition to the above measures, suitable protective systems to protect the water against contamination can be considered. Protective systems to prevent spilled hazmat from reaching the water can be provided. However, they are very expensive and hence they need to be provided only if really necessary. However, improving response and providing training to response personnel to handle such events can reduce the damage to a great extent. According to the survey, the following mitigation measures can be considered for the above scenario, if found necessary by the officials.

Protective Systems

- Drainage gutters to direct spilled material toward collection point
- Design clay blankets or barrier membrane; direct drainage away from sensitive areas
- Floating surface barrier (for insoluble petroleum oils)
- Robust drainage with holding reservoirs that can be isolated from regular storm drains should a spill occur
- Large sumps
- Retention basins that can automatically close to capture spillage
- Grease trap sedimentation basin (for heavier insolubles)

Regulatory Measures

- Insure inspection and regulation of storage facilities

Thus, it can be seen that the measures to be provided to mitigate hazardous material risks are very site specific. The measures obtained through this research has to be expanded in course of time as technology becomes available. The effectiveness of the protective systems has to be compiled as they are implemented. The effectiveness provided in this research are based on the opinion of experts and can be used as guidelines in the selection of different measures.

7.0 CONCLUSIONS

The risk due to transportation of hazardous materials has been a cause of concern in the recent years due to the increase in the shipment of these materials. Though the probability of an accident is very low, the consequences could be potentially severe because of the population, property exposed. The concept of reducing risk due to transportation of hazardous materials is a relatively new topic and hence this research has limitations of insufficient literature, data etc. However, in this study, a methodology is presented in an attempt to overcome the problems and come up with alternative solutions. Some of the solutions recommended are not available at present. However, these are recommended in the light of recent technological advances.

The different scenarios arrived at based on the responses of the states' personnel and the protective measures arrived at should form guidelines in the implementation of risk reduction strategies. Based on the responses, it can be concluded that regulatory type preventive measures dominated suggested solutions. This implies that 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 risk is deemed high enough to offset the cost.

The geometric design elements requiring special attention on high risk hazmat routes should not be overlooked as preventing one accident could mean a potential

saving of several lives. These geometric elements affect the transportation of trucks. Though it is not possible to address the other elements in this research, it is emphasized that they meet the requirements of AASHTO.

7.1 Recommendations for Further Research

It is recommended that suitable changes be made in the data collection. Data forms a key to any analysis and lack of suitable data results in a model with several assumptions and limitations. The risk model presented here uses all truck accidents as data on hazmat flows are not available. Also, national default values on probability of release is taken because of the same reason. This has to be modified in course of time by acquiring similar data in region considered.

In the mitigation measures, improvements has to be made in the effectiveness of geometric design elements. This has to be substituted by truck accident reduction factors. Also, further research has to be undertaken in expanding the protective systems as technology becomes available and also in determining the cost-effectiveness. This aspect requires data which is not available at present. The application of the protective systems on different scenarios has to be studied in detail and actual effectiveness has to be determined.

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Appendix A. SURVEY QUESTIONNAIRES AND RESULTS

The different survey questionnaires used in order to obtain effectiveness of consequence reduction measures and the results obtained have been included in the survey. Delphi-panel technique is used in this research. The survey is carried out in many rounds. The results obtained in the first round are summarized and sent out again to the panelists to get their comments and revisions. The revisions obtained are again compiled and mailed until a consensus is reached.

The physical protective systems have been sent out first and they are compiled followed by regulatory measures. In this appendix, the forms used and the final results obtained are attached.

TO: Panel Members

From: Dr. Russell, Dr. Hobeika, Raja Sethuraman, Sigon Kim

There are two parts of risk reduction:

1) Accident reduction, and
2) Consequence reduction

We have uncovered accident reduction relationships between accident rates and improved highway geometrics for all vehicles but we believe that there is no reliable data in the literature to relate truck accidents to highway elements. If you know of any please let us know.

Following is a list of protective system measures that a panel of states' personnel came up with. We would like your estimate (your best "guess" is all we ask for) of the percentage reduction in consequence for each protective system. For example, let's take a high risk situation where hazmat trucks are having accidents and releases on freeway off-ramps. The consequence will be a function of probability of a release and release rate (slow or sudden release). High strength barrier rail designed to contain and redirect 80,000 lb tank trucks should reduce both the accident severity and the probability of a release (given an accident). The question is - how much ? Would it be 75%, 50%, 25% or some other value?

We don't expect exact answers. There will be no verifiable data to give answers until we have tried these protective systems and recorded results for a number of years. The collective opinion of a panel of knowledgeable experts such as you, could give us valuable insight into a "ball park" number as a starting point. Would you please try. Your individual responses will be kept strictly confidential.

After each protective system put two numbers"

1) The consequence % reduction, e.g., 80%, 50%, 10%, and
2) Self rate your answer on a 1 to 10 scale with one being strictly a guess, and 10 being a case where you are sure of your answer. For estimates, you would self rate as guesses, use something lower than "5". For estimates you are confident and reasonable, use something greater than "5".

Example: I don't know how much about the effects of hazmat truck releases on ramps. I will guess 50 %. It is strictly a wild guess so I'll put a "1" after the guess. If I have reason to believe 50% is a very reasonable value. I might put a "7" after the estimate. If I feel very strongly that 50% would be valid, I would put "9" or "10"

The average, collective results of the responses will provide valuable nput to a starting point in a cost effectiveness analysis of these protective systems. We need and value your input. Mark the two numbers right after the protective system on the form and return to us.

Protective system rating results of all proposed protective systems rate 4.0 or greater by the panel.

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*		Consequence Reduction Estimate %(0 - 100)	Answer Confidence Self rating 1 - 10
1	Traversable medians	_____	_____
2	Emergency phone call boxes on all hazardous cargo routes	_____	_____
3	Crossovers	_____	_____
3	Median openings	_____	_____
4	Highway exits designed for traffic entrance (response team) from opposite direction	_____	_____

SCENARIO 2 -- Chemical spills of poisonous or explosive materials that could enter background "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*		Consequence Reduction Estimate %(0 - 100)	Answer Confidence Self rating 1 to 10
1	Fresh air vents at elevated levels	_____	_____
1	Prohibition in areas; air vents-- intakes away from roads, arrows in tunnels with distance to exit, etc.	_____	_____
3	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	Pea-trap system vents to trap gases in first section	_____	_____

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

Protective Systems-type Solutions Rank*		Consequence Reduction Estimate %(0 - 100)	Answer Confidence Self rating 1 - 10
1	Arrows pointing to nearest exit	_____	_____
2	Effective vent systems	_____	_____
3	Monitoring for quick response	_____	_____

*Rank order is how these sytems were ranked previously by this panel.

4	Gas detectors/alarm systems	_____	_____
5	Large sprinkler systems	_____	_____
6	Emergency exits with heavy doors	_____	_____

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*		Consequence Reduction Estimate %(0 - 100)	Answer Confidence Self rating 1 - 10
1	High performance barrier/rail systems to prevent such an accident	_____	_____
2	Avoid use of open rails on structure	_____	_____
3	Robust drainage with holding reservoirs that can be isolated from regular storm drains (and later pumped) should a spill occur	_____	_____
4	Conduit railing for automatic spraying of water	_____	_____
4	Relocate or close ramps--in critical locations; install improved barriers; prohibit truck use of such ramps	_____	_____

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*		Consequence Reduction Estimate %(0 - 100)	Answer Confidence Self rating 1- 10
1	Communication and detection systems	_____	_____
2	Development of a public notification system for efficient evacuation possibly using air raid type alarms and public address systems.	_____	_____

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		Estimate	Self rating
1	Installing effective barriers between parallel transport corridors	_____	_____
2	Shared rights-of-way should be separated by concrete barriers	_____	_____
3	Higher, stronger, etc., barriers next to transit	_____	_____

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 conflagration.

Protective Systems-type Solutions Rank*		Consequence Reduction Estimate %(0 - 100)	Answer Confidence Self rating 1 - 10
1	Communication and detection systems	_____	_____

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*		Consequence Reduction Estimate %(1 - 100)	Answer Confidence Self rating 1- 10
1	Drainage gutters to direct spilled material toward collection point	_____	_____
2	Design with clay blanket or barrier membrane; direct drainage away from sensitive areas	_____	_____
3	Floating surface barrier (for insoluble petroleum oils)	_____	_____
4	Robust drainage with holding reservoirs that can be isolated from regular storm drains should spill occur	_____	_____
5	Large sumps	_____	_____
5	Retention basin that can automatically close to capture spillage	_____	_____
6	Grease trap sedimentation basin (for heavier insolubles)	_____	_____

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*		Consequence Reduction Estimate %(0 - 100)	Answer Confidence Self rating 1 - 10
1	Truck escape ramp	_____	_____
2	Upgrade runoffs for deceleration and extra-wide shoulders	_____	_____
3	Construct massive barrier and put energy absorbing material in front	_____	_____

Comments: Any comments you wish to make would be appreicated (either on the relationship between improving geometric elements and truck accident rates or reduction of consequences w/protective systems).

Department of Civil Engg.
Seaton Hall
Kansas State University
Manhattan, KS 66506
(913) 532-5862
November 21, 1989

&Name/O&
&Company/O&
&City/O&
&State/O&
&Zip/O&

Dear &First/O&:

Most of the panel has responded to the previous mailing requesting effectiveness values for physical protective systems. I have summarized the results and these are included here is for your information.

In the Delphi technique, a consensus is sought. The purpose of this round is to attempt to move toward a consensus by asking if you can accept the average value of the first round, or suggest an adjustment. The adjustment may be sticking with your original value or some new, revised value.

Thus, if you can accept the value, put a check in the proper space. If not, put your value in the blank space.

Also with this mailing I am including round 1 of evaluating the effectiveness of regulatory protective systems. Answer this one in the same manner that you did the first, i.e., rate the effectiveness on a 100% scale, then self rate your answer on a 1 to 10 scale with 1 being strictly a guess and 10 being an answer you would feel confident is a correct value. Return in the addressed, stamped envelope.

Your cooperation is very much appreciated. You are making an important contribution to a new area. Note also, we are still seeking data relating truck accidents to geometric elements of highways. Please let me know if you have or know of such data.

Yours truly,

Eugene R. Russell, Sr.

ERR:tkh

PS - If you are not interested or do not have the time to participate in this expert evaluation process, please return this letter with your name and we will remove your name.

Please mark blank colums and return

A. FIRST ROUND SUMMARY

Consequence Reduction Estimate For Physical Protective Systems

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 Ranks*		Summary Consequence Reduction Estimate %(0 - 100)	Check here if you can except this value	Value you could except
1	Traversable medians	50		
2	Emergency phone call boxes on all hazardous cargo routes	25		
3	Crossovers	30		
3	Median openings	30		
4	Highway exits designed for traffic entrance (response team) from opposite direction	30		

SCENARIO 2 -- Chemical spills of poisonous or explosive materials that could enter background "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 Ranks*		Summary Consequence Reduction Estimate %(0 - 100)	Check here if you can except this value	Value you could except
1	Fresh air vents at elevated levels	50		
1	Prohibition in areas; air vents-- intakes away from roads, arrows in tunnels with distance to exit, etc.	50		
3	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.	45		
3	Pea-trap system vents to trap gases in first section	40		

*As ranked by panel

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

Rank*	Protective Systems-type Solutions	Summary Consequence Reduction Estimate %(0 - 100)	Check here if you can except this value	Value you could except
1	Arrows pointing to nearest exit	30		
2	Effective vent systems	45		
3	Monitoring for quick response	50		

*Rank order is how these sytems were ranked previously by this panel.

4	Gas detectors/alarm systems	35		
5	Large sprinkler systems	30		
6	Emergency exits with heavy doors	25		

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.

Rank*	Protective Systems-type Solutions	Summary Consequence Reduction Estimate %(0 - 100)	Check here if you can except this value	Value you could except
1	High performance barrier/rail systems to prevent such an accident	60		
2	Avoid use of open rails on structure	45		
3	Robust drainage with holding reservoirs that can be isolated from regular storm drains (and later pumped) should a spill occur	40		
4	Conduit railing for automatic spraying of water	25		
4	Relocate or close ramps--in critical locations; install improved barriers; prohibit truck use of such ramps	60		

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.

Rank*	Protective Systems-type Solutions	Summary Consequence Reduction Estimate %(0 - 100)	Check here if you can except this value	Value you could except
1	Communication and detection systems	50		
2	Development of a public notification system for efficient evacuation possibly using air raid type alarms and public address systems.	50		

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.

Rank*	Protective Systems-type Solutions	Summary Consequence Reduction Estimate %(0 - 100)	Check here if you can except this value	Value you could except
1	Installing effective barriers between parallel transport corridors	60		
2	Shared rights-of-way should be separated by concrete barriers	60		
3	Higher, stronger, etc., barriers next to transit	65		

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 conflagration.

Rank*	Protective Systems-type Solutions	Summary Consequence Reduction Estimate %(0 - 100)	Check here if you can except this value	Value you could except
1	Communication and detection systems	50		

SCENARIO 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.

Protective Systems-type Solutions Rank*		Summary Consequence Reduction Estimate %(0 - 100)	Check here if you can except this value	Value you could except
1	Drainage gutters to direct spilled material toward collection point	60		
2	Design with clay blanket or barrier membrane; direct drainage away from sensitive areas	60		
3	Floating surface barrier (for insoluble petroleum oils)	45		
4	Robust drainage with holding reservoirs that can be isolated from regular storm drains should spill occur	55		
5	Large sumps	50		
5	Retention basin that can automatically close to capture spillage	55		
6	Grease trap sedimentation basin (for heavier insolubles)	40		

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*		Summary Consequence Reduction Estimate %(0 - 100)	Check here if you can except this value	Value you could except
1	Truck escape ramp	70		
2	Upgrade runoffs for deceleration and extra-wide shoulders	60		
3	Construct massive barrier and put energy absorbing material in front	30		

Comments: Any comments you wish to make would be appreciated (either on the relationship between improving geometric elements and truck accident rates or reduction of consequences w/protective systems).

Consequence reduction estimate

Scenario	Response Number 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	Sum $\bar{X}$	S
1	40	60	40	50	50	10	60	85	40	50	60	25	50	50	50	75	25	25	75	920/48.4	19.0
	20	70	0	15	20	5	0	15	60	10	10	20	20	10	80	50	25	50	10	500/26.3	24.1
	20	50	—	10	50	10	20	55	30	30	30	25	10	50	50	40	25	25	50	580/32.2	15.6
	20	40	10	10	40	10	20	55	20	30	30	20	10	50	60	40	25	25	60	575/30.3	17.0
	80	60	20	0	10	10	0	30	50	40	20	20	10	80	9	25	10	25	60	555/29.4	25.3
2	50	90	50	40	75	20	50	50	60	70	30	30	50	70	80	50	20	50	—	935/51.9	19.8
	30	90	30	—	70	20	50	55	50	80	20	50	30	50	90	60	25	50	—	850/50.0	22.7
	60	90	50	50	20	10	50	50	70	50	20	35	30	50	60	50	10	25	—	780/43.3	21.2
	50	40	10	40	20	10	50	70	60	40	30	45	30	50	60	40	10	50	—	705/39.2	17.8
3	30	30	5	10	10	10	10	65	60	10	35	50	20	10	50	70	10	25	10	520/27.4	21.6
	60	30	20	25	50	20	50	75	30	60	75	30	30	70	90	50	25	25	70	835/46.5	22.2
	80	50	50	50	20	20	50	45	50	20	25	60	30	50	90	50	25	75	60	900/47.4	20.5
	60	50	30	25	35	20	30	45	20	30	20	25	30	10	50	40	10	50	70	650/34.2	16.4
	60	60	30	15	20	20	30	75	10	20	20	30	20	10	60	40	50	25	20	615/32.4	19.4
	20	30	5	10	25	10	30	50	10	30	40	25	20	10	20	30	10	25	30	430/22.6	11.7
4	80	70	50	60	50	20	50	85	60	60	60	40	50	70	80	75	50	50	80	1140/60.0	16.4
	50	60	60	20	20	10	0	60	70	40	—	25	20	50	75	60	10	75	70	775/43.1	25.1
	60	90	30	40	10	30	10	70	40	70	30	20	10	70	30	50	10	25	40	735/38.7	23.9
	50	90	1	15	10	5	10	50	20	20	30	15	10	10	40	40	5	25	30	485/25.6	22.5
	40	90	80	20	20	20	40	80	80	100	40	15	90	80	80	60	75	75	75	1160/61.1	28.0
5	80	80	30	60	20	10	0	70	60	50	65	50	50	50	75	80	50	25	75	980/51.6	24.4
	60	40	40	60	50	10	0	65	80	70	75	35	50	80	75	70	25	50	80	985/51.8	22.8
6	50	90	80	80	25	5	50	75	70	90	60	50	50	70	80	70	50	50	80	1175/61.8	22.0
	50	90	80	80	25	5	50	80	50	90	75	50	60	70	60	60	10	50	90	1125/59.2	25.2
	80	90	80	80	25	5	50	80	60	90	75	50	60	70	75	60	50	50	90	1220/64.2	22.6
7	70	20	20	20	50	60	0	75	50	50	70	40	50	10	80	70	50	50	80	915/48.2	24.2
8	70	80	90	90	5	60	10	90	50	70	75	40	70	50	65	75	10	50	90	1140/60.0	27.4
	70	90	70	90	5	40	10	85	60	60	70	50	70	50	75	60	10	50	90	1105/58.2	26.5
	50	80	20	40	10	30	50	75	80	60	60	40	20	50	60	50	10	25	10	820/43.2	23.7
	50	90	95	50	50	40	10	85	70	80	70	40	70	50	80	50	10	50	30	1070/56.3	24.6
	50	90	80	75	25	40	10	60	—	60	65	20	10	50	70	40	50	25	30	850/47.2	24.0
	70	90	50	50	20	40	10	80	80	60	70	25	50	50	70	50	50	25	70	1010/53.2	22.1
	50	80	20	50	10	40	10	80	60	40	55	20	30	50	60	50	50	25	10	790/41.6	21.7
9	80	70	60	80	75	20	50	75	90	70	80	60	80	90	90	80	50	50	90	1340/70.5	18.3
	80	70	80	60	75	50	20	75	50	50	75	50	20	70	90	60	50	25	90	1140/60.0	21.6
	50	40	5	20	20	10	10	45	70	40	50	5	40	20	30	50	10	25	50	590/31.1	19.0

Please mark blank columns and return

B. REGULATORY PROTECTIVE SYSTEMS

Regulatory system rating results all proposed protective systems rated 4.0 or greater.

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.

Regulatory Systems-type Solutions Rank*		Consequence Reduction Estimate %(0 - 100)	Answer Confidence Self rating 1 - 10
1	Routing restrictions	_____	_____
2	Prohibition on hours (curfews)	_____	_____
2	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.

Regulatory Systems-type Solutions Rank*		Consequence Reduction Estimate %(0 - 100)	Answer Confidence Self rating 1 - 10
1	Restricted routing in these areas	_____	_____

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

Regulatory Systems-type Solutions Rank*		Consequence Reduction Estimate %(0 - 100)	Answer Confidence Self rating 1 - 10
1	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.

Regulatory Systems-type Solutions Rank*		Consequence Reduction Estimate %(0 - 100)	Answer Confidence Self rating 1 - 10
1	Reduced speed	_____	_____
2	No hazmat through high urban area (prohibition)	_____	_____

* As ranked by panel.

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.

Regulatory Systems-type Solutions Rank*		Consequence Reduction Estimate %(0 - 100)	Answer Confidence Self rating 1 - 10
1	Evacuation planning	_____	_____
2	Emergency response training	_____	_____
3	Reduced speed with strict enforcement	_____	_____
4	Routing/prohibition	_____	_____
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.

Regulatory Systems-type Solutions Rank*		Consequence Reduction Estimate %(0 - 100)	Answer Confidence Self rating 1 - 10
1	Specific training for fire department, police, etc.	_____	_____
2	State-of-art crossing warning systems	_____	_____
3	Reduced train speeds in urban areas	_____	_____
4	Sufficient warning indicators installed reasonably well in advance of crossings	_____	_____
5	Restricting hazmat transportation routes to avoid high hazard areas	_____	_____
6	Law requiring full stop before crossing	_____	_____

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 petrochemical plant that could result in conflagration.

Regulatory Systems-type Solutions Rank*		Consequence Reduction Estimate %(0 - 100)	Answer Confidence Self rating 1 - 10
1	Increase inspections	_____	_____
2	Insure inspection and regulation of storage facilities	_____	_____

SCENARIO 7 continued

3	Escort vehicle for explosives	_____	_____
3	Control speed	_____	_____
5	Mandate restrictive zoning prohibiting certain chemical storage/processing around certain traffic/population density situations	_____	_____
5	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	_____	_____
5	Routing/prohibition	_____	_____
6	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 released into a potable water supply, particularly reservoirs and susceptible aquifers and/or watersheds.

Regulatory Systems-type Solutions Rank*		Consequence Reduction Estimate %(0 - 100)	Answer Confidence Self rating 1 - 10
1	Insure inspection and regulation of storage facilities	_____	_____

SCENARIO 9 -- None

B. REGULATORY PROTECTIVE SYSTEMS (Results)

Regulatory system rating results all proposed protective systems rated 4.0 or greater.

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.

Regulatory Systems-type Solutions Rank*		Consequence Reduction Estimate %(0 - 100)	Answer Confidence Self rating 1 - 10
1	Routing restrictions	64.4	
2	Prohibition on hours (curfews)	45.3	
2	Prohibit large trucks through congested areas (routing)	55.8	

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.

Regulatory Systems-type Solutions Rank*		Consequence Reduction Estimate %(0 - 100)	Answer Confidence Self rating 1 - 10
1	Restricted routing in these areas	69.7	

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

Regulatory Systems-type Solutions Rank*		Consequence Reduction Estimate %(0 - 100)	Answer Confidence Self rating 1 - 10
1	Routing hazmats away from tunnels (prohibition)	80.8	

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.

Regulatory Systems-type Solutions Rank*		Consequence Reduction Estimate %(0 - 100)	Answer Confidence Self rating 1 - 10
1	Reduced speed	41.7	
2	No hazmat through high urban area (prohibition)	73.6	

* As ranked by panel.

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.

Regulatory Systems-type Solutions Ranks		Consequence Reduction Estimate %(0 - 100)	Answer Confidence Self rating 1 - 10
1	Evacuation planning	51.90	
2	Emergency response training	50.0	
3	Reduced speed with strict enforcement	43.1	
4	Routing/prohibition	73.5	
4	Training of personnel of schools, hospitals, hotels, nursing homes	51.4	

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.

Regulatory Systems-type Solutions Ranks		Consequence Reduction Estimate %(0 - 100)	Answer Confidence Self rating 1 - 10
1	Specific training for fire department, police, etc.	45.0	
2	State-of-art crossing warning systems	48.3	
3	Reduced train speeds in urban areas	40.8	
4	Sufficient warning indicators installed reasonably well in advance of crossings	42.2	
5	Restricting hazmat transportation routes to avoid high hazard areas	65.3	
6	Law requiring full stop before crossing	40.3	

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 petrochemical plant that could result in conflagration.

Regulatory Systems-type Solutions Ranks		Consequence Reduction Estimate %(0 - 100)	Answer Confidence Self rating 1 - 10
1	Increase inspections	43.1	
2	Insure inspection and regulation of storage facilities	48.6	

SCENARIO 7 continued

3	Escort vehicle for explosives	35.0	
3	Control speed	37.9	
5	Mandate restrictive zoning prohibiting certain chemical storage/processing around certain traffic/population density situations	62.2	
5	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	57.8	
5	Routing/prohibition	66.1	
6	Thermal protective coverings on packages	38.9	

SCENARIO 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.

Regulatory Systems-type Solutions Rank*		Consequence Reduction Estimate %(0 - 100)	Answer Confidence Self rating 1 - 10
1	Insure inspection and regulation of storage facilities	51.1	

SCENARIO 9 -- None

Appendix B. SURVEY FORMS USED TO COLLECT DATA

The data required for mitigation on the highway segments are collected using a survey form. The form used has the required geometric design check and the high catastrophic scenario check. In addition it is necessary to get some additional details on the hazardous elements which could cause accidents on highway. The other details such as population, property etc., has to be obtained from the local census bureau and other public agencies.

SURVEY FORM

County: _____ Municipality: _____

St_Route No: _____ Segment: _____

Highway type: _____ Area type: _____

Geometry Data

Lane width _____

Shoulder width _____

Shoulder type _____

Degree of curvature _____

Sight distance _____

Vertical grade _____

Bridge width _____

Clear roadside recovery _____

Median/Median barrier _____

Type of Scenario

See attached list _____

Comments

GENARILIZED POTENTIALLY EXTREME RISK SITUATIONS

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.

2) Chemical spills of poisonous or explosive materials that could enter background "METRO" stations or transit tunnels through side-walk 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 there-to, 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) Releases from accidents between hazardous materials containers on highways and passenger trains or trains causing 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.

7) Explosive materials in facilities in populated areas 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 related 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 material carriers could cause catastrophic consequences to the populated areas.

Consequence Data (within the impact area)

Residential population density _____

Employment population density _____

# of Commercial units _____

# of Office units _____

# of Industrial units _____

Retail _____

Farms _____

Schools _____

Enrollment _____

Hospitals _____

of In-patients _____

Total quantity of water _____

Appendix C. ACCIDENTS AND ROADWAY FEATURES

The items below are not claimed to be a complete list of all possible highway safety measures, nor should they be considered exclusively for hazmat routes. Safety measures of this type should be given extra consideration on the high risk hazmat routes. These elements contribute to the risk reduction by reducing the probability of the accident and its severity.

Run off the road type accidents:

- Effective signing and delineation, especially on horizontal curves.
- Wider lanes, curve widening.
- Higher skid resistances.
- Shoulder roughening or rumble strips.

Head-on collision type accidents:

- Median barriers.
- Wider lanes.
- One-way travel or separation of lanes.
- Crash cushions for fixed objects.

Rear-end collision accidents:

- Access control.
- Longer weaving areas.

- Longer acceleration lanes.
- Climbing lanes for slow vehicles. .
- Intersection channelization.
- Improved intersection sight distance.
- Increased surface friction.

Angle collisions:

- Access control.
- Intersection channelization.
- Improved intersection signal controls.
- Longer weaving areas.
- Lane delineation.

Overturn accident:

- Improved shoulders.
- Smooth pavement edge joints.
- Flatter embankments > = 6:1
- Wider clear zones > = 30ft.
- Wide, traversable medians or median barrier.
- Impact resisting road barrier.
- Improved curve design.
- State-of-the-art ramp design with longer deceleration lanes and improved delineation.

Vita

Mr. Rajagopal Sethuraman was born on November 5, 1966 in Vijayawada, India. He was brought up in Hyderabad, where he did most of his schooling. Later, he joined Osmania University in order to pursue a career in engineering. He obtained Bachelor's degree in Civil Engineering in July 1987. After graduating, he started working in a private consulting firm in Hyderabad, India. He joined Virginia Polytechnic Institute & State University in Fall 1988 for Master's program in Civil Engineering with Transportation as major. Upon graduation, he will be working in a traffic/transportation engineering firm in order to gain practical experience.

S. Rajagopal