U. S. Department
of Transportation
**Federal Railroad
Administration**

A Review of Risk Analysis Methodologies Used in Evaluating Railroad Systems Safety

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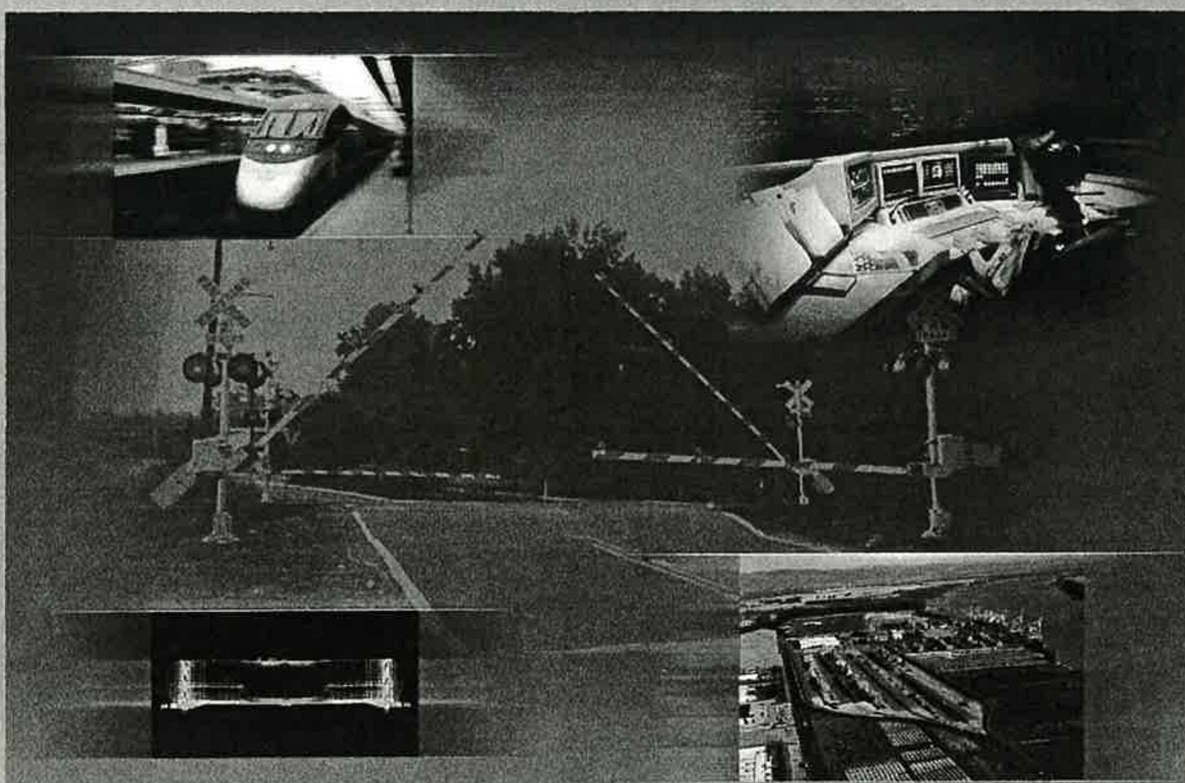
Washington, DC 20590



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13. ABSTRACT (Maximum 200 words)

This study was undertaken to review the various risk analysis models developed under FRA and the Volpe National Transportation Systems Center sponsorship and is applicable to evaluating the risks associated with railroad operations. Railroad risk models developed over the past decade by other institutions and risk models applicable to other transportation modes also were reviewed.

All railroad risk models have basic similarities in the approach in that probabilities and consequences are evaluated. However, great differences lie in the spectrum and the level of aggregation of the accident scenarios and the methods used to calculate the potential consequences. In some models, historical accident data are used to perform statistical correlation analysis and to predict top level scenarios for the system using its operational metrics. In other cases fault tree type assessment is done using conditional probabilities of sub-system and component failures. Casualties are either estimated or calculated using finite element models to predict the crushing of passenger cars and their effect on the passenger fatality and injury. It is seen that intermediate complexity models do just as well in predicting the risks. None of the models reviewed directly evaluated the effectiveness of current regulations in risk reduction. Many models do not provide estimates of the confidence level of the results.

Several recommendations are provided to enhance the current models and make them more applicable to railroad system risk assessment.

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PREFACE

The work described in this report was performed by Technology & Management Systems, Inc., (TMS) under Contract DTRS57-99-P-80813 from the U.S. Department of Transportation, John A. Volpe National Transportation Systems Center, Cambridge, MA. Robert Dorer of the Railroad Systems Division was the Contracting Officer's Technical Representative on this project. Phani K. Raj was the Project Manager, the principal investigator for this project at TMS. He is also the author of this report. The funding for this contract was provided by the Federal Railroad Administration's (FRA) Office of Research and Development. The FRA's Railroad Systems safety program is managed by Claire Orth, Chief of Equipment and Operating Practices Research Division.

The Project Manager at TMS expresses his thanks to the stimulating technical discussions, guidance and support provided by Robert Dorer.

The Volpe Center would like to extend credit to Ackroyd Photography and the Union Pacific Railroad for submitting cover graphics for this report.

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

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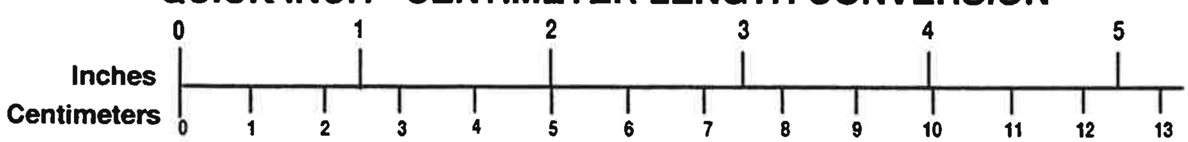
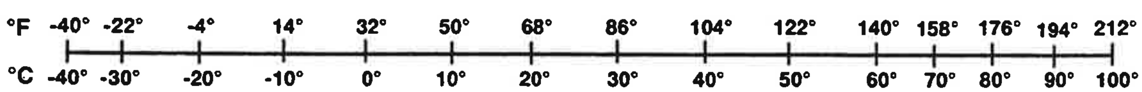


QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION



For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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LIST OF ACRONYMS

AAR	Association of American Railroads
ABS	Automatic Block Signaling
ALARP	As Low As Reasonably Practical (A risk criterion)
ARES	Advanced Railroad Electronics System
ATC	Advanced Train Control
BN	Burlington Northern
bpm	Billion Passenger Miles
CMA	Chemical Manufacturing Association
CPU	Central Processor Unit (of a computer)
CSDL	Charles Stark Draper Laboratory
CRAM	Corridor Risk Assessment Model
DOT	U.S. Department of Transportation
EMF	Electromagnetic Field(s)
EMI	Electromagnetic Interference
FCR	Fatality-to-Casualty Ratio
FRA	Federal Railroad Administration
HSE	Health and Safety Executive (of Britain)
HSR	High-Speed Rail
HST	High-Speed Train
LPG	Liquefied Petroleum Gas
MAS	Maximum Allowed Speed

LIST OF ACRONYMS (cont.)

MIT	Massachusetts Institute of Technology
MOW	Maintenance-of-Way
MTM	Million Train Miles
NIST	National Institute of Standards and Technology
NTSB	National Transportation Safety Board
PIH	Poison by Inhalation (a hazardous) material
PSCI	Perceived Safety Cost Index
PTC	Positive Train Control
PTS	Positive Train Separation
RCF	Risk Conversion Factor
ROW	Right-of-Way
RPI	Railway Progress Institute
RSAC	Railroad Safety Advisory Committee
SCI	Safety Cost Index
U.S.	United States
VHF	Very High Frequency
Volpe Center	Volpe National Transportation Systems Center
WIU	Wayside Interface Units

EXECUTIVE SUMMARY

This study was undertaken to review the various risk analysis models developed under Federal Railroad Administration and Volpe National Transportation Systems Center sponsorship and applicable to evaluating the risks associated with railroad operations. Railroad risk models developed over the past decade by other institutions and risk models applicable to other transportation modes were also reviewed.

One of the strategic goals of the U.S. Department of Transportation is to foster safety and to "promote the public health and safety by working toward the elimination of transportation-related deaths, injuries, and property damage." Each safety outcome goal will be measured by the reductions in both the absolute number and the rate (expressed as number per passenger mile or ton mile for freight) of transportation-related deaths, number and severity of transportation-caused injuries and the cost of loss from high consequence, reportable transportation incidents.

This study addresses: (1) risk assessment methodologies relevant to railroad operations; (2) risk evaluation approaches in other similar industries; and (3) lessons learned in using risk analysis methods in other industries that can be effectively used in railroad systems.

In one quantitative representation, risk is defined as the probability of an event occurring which has a detrimental effect on either people or property. In other cases, risk represents the frequency of occurrence of an "average magnitude" detrimental effect (of all possible magnitudes of detrimental effects). The problem with defining risk by the frequency of occurrence of an "average magnitude" event is that it is easy to miss considering large consequence events and determining whether they occur frequently, rarely or extremely rarely.

The research on the risks in railroad systems has been conducted at three distinct levels of complexity. The first level is the collection of data on railroad accidents from both U.S. and foreign operations for low-speed and high-speed trains and using these data to determine what the specifications should be for the various subsystem performance in a new railroad system. The focus of the first level of research is the development of simple risk analysis approaches useful for the generation of performance specifications. In the second level, screening type of risk analysis studies have been conducted. In the third level, detailed operational conditions, signal systems and vehicle dynamics are taken into account to calculate overall risks in specific corridors with other traffic on shared rights-of-way.

Several risk assessment projects and models related to the transportation of passengers on railroads have been reviewed. Specific attention was focused on the application of the models to determining the risks in railroad systems. Also reviewed were some of the basic concepts of risks and society's perception and acceptability of risks in regard to transportation and other technological systems.

The study found a large variation in the amount of details used to evaluate risks and several different representations of the risk results. There are considerable differences in how risk is perceived by different segments within an affected population. The methodologies used in the U.S., in general, tend to include only the societal risk whereas the methodologies used in Europe and Japan include both the societal and individual risk in determining risk acceptability. In many risk analysis calculations, the results are presented without any discussion of the confidence levels associated with the results. This fact makes it difficult for decision makers to interpret the results and implement remedial action.

Subjective measures of risk may not be sufficient to implement new regulations; in some situations more rigorous, quantitative magnitudes for risk acceptability may need to be defined. Some risk analysis models show promise for determining the risks in high-speed rail systems; however, additional modeling refinements will provide improved rigor in the analysis process.

1. BACKGROUND

1.1 INTRODUCTION

One of the strategic goals of the U.S. Department of Transportation (U.S. DOT) is to foster safety and to "promote the public health and safety by working toward the elimination of transportation-related deaths, injuries, and property damage."[1] Each safety outcome goal will be measured by the reductions in both the absolute number and the rate (expressed as number per passenger mile or ton mile for freight) of transportation-related deaths, number and severity of transportation-caused injuries and the cost of loss from high consequence, reportable transportation incidents.

The Federal Railroad Administration (FRA) has been charged by Congress to "promote safety in areas of railroad operations, reduce railroad accidents, and reduce deaths and injuries to persons and damage to property caused by accidents involving any carrier of hazardous materials."[2] Other legislation required the FRA to ensure the safety of workers going between rail cars,[3] qualify railroad engineers,[4] and reduce the fatalities at rail-highway grade crossings.[5] In response to these acts, the FRA has issued a number of rules covering a wide spectrum of safety issues in the transportation of passengers and freight (especially the hazardous materials). Most of these regulations were specification-oriented and contained civil penalties for violation of the rules. In the early 1990s, the FRA instituted two important changes in its regulatory policy. One involved the approach to enforcing the rules. Instead of using civil penalties as a means to ensure compliance with railroad safety regulations, the FRA decided to emphasize cooperative partnerships with other federal agencies, railroad management, labor unions and the states.[6] The second important change involved the development of performance-oriented regulations. Extensive use of risk analysis techniques and methods in the development of regulations was initiated. Many regulations promulgated in the 1990s have been based on the application of risk analysis techniques and their results (Raj and Pritchard, 2000). One such application of risk

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[1]U.S. Department of Transportation, Strategic Plan 1997-2002, September 30, 1997, Washington D.C. Specifically in regard to rail operations, the DOT five-year plan calls for the reduction in 1995 casualty rates to the following values in the year 2000: (1) rail-related fatalities from 1.71 per million train miles (MTM) to 1.3 per MTM, (2) rail-related crashes from 3.91 per MTM to 3.32 per MTM, and (3) grade-crossing crashes from 2.85 per the product of MTM and trillion highway vehicle-mile-travel to 2.56 per the product of MTM and trillion highway vehicle-miles-traveled.

[2]Federal Railroad Safety Act of 1970; Hazardous Materials Transportation Act of 1974; Hazardous Materials Transportation Uniform Safety Act of 1990.

[3]Federal Railroad Safety Authorization Act of 1976.

[4]The Rail Safety Improvement Act of 1988.

[5]Highway Safety Acts of 1973 and 1976; Surface Transportation Acts of 1978 and 1982.

[6]Testimony before Congress by Ms. Phyllis Scheinberg, Associate Director, Transportation Issues, Resources, Community, and Economic Development Division, The General Accounting Office, May 20, 1998.

analysis techniques has been to evaluate the safety impact of new transportation systems proposed for deployment on the U.S. intercity railroad systems.

The FRA and the Volpe National Transportation Systems Center (Volpe Center) have sponsored and conducted research evaluating the technologies and safety issues related to passenger transportation in high-speed, inter-city railroad systems. The assessment of risks to passengers and third parties due to rail accidents, analysis of crashworthiness of train coaches, fire safety and emergency egress issues, effectiveness of positive train control (PTC) systems, grade crossing enhancement, etc. are part of these research activities. In many of these studies, various risk analysis methodologies have been employed. These risk analysis studies have ranged from high level fault tree analyses of a new magnetic levitation system (Transrapid) to issues surrounding applications of mature high-speed rail technologies (such as the French TGV train) in the U.S. environment. Studies have also been conducted to determine the issues and potential risk mitigation needs or effects of sharing of railroad and other transportation mode rights-of-way, joint usage of tracks by freight and passenger trains and PTC systems. In addition, focused studies on topics such as collision avoidance and accident survivability have been carried out from the risk determination perspective. Major safety assessments have been carried out by other overseas institutions and railroads not only from the perspective of reducing potential accidents and passenger and crew fatalities and injuries, but also in determining the optimal way to apply scarce monetary resources to achieve the maximum level of safety.

The application of risk assessment methodologies to understand risk and design systems to eliminate or reduce the frequency and magnitude of accidents in passenger-carrying rail systems has been going on for over a decade. However, a comprehensive review of these studies indicates that these results have not been used in developing national policies or promulgating regulations or making strategic or tactical decisions by government and the railroad industry. Such an evaluation is the purpose of this study.

1.2 OBJECTIVES OF THIS STUDY

The objective of this study is to examine the following topics:

- Risk assessment methodologies for railroad systems.
- Risk evaluation approaches in other similar industries.
- Lessons learned in using risk analysis methods in other industries that can be effectively used in railroad systems.

An additional objective is to summarize past FRA risk analysis initiatives and present them in the perspective of the overall FRA goal of ensuring (and enhancing) railroad safety while embracing new technology.

1.3 WORK ACCOMPLISHED

In order to achieve the above objective, a review of the following topics was conducted:

- General risk analysis principles, approaches and methodologies.

- Risk analysis and other relevant safety-related research conducted under the sponsorship of the FRA and Volpe for railroad systems.

- Research for railroad systems risks performed by other institutions.

The general principles of risk analyses, risk concepts, magnitudes of risk in several activities that the general population engages in, methodologies, etc. are briefly discussed in Section 2. The risk analysis efforts by FRA-funded projects, other rail transportation systems, and other related (transportation) institutions are reviewed in Section 3. The lessons learned from these investigations are also discussed in the same chapter. The conclusions and recommendations resulting from this study are continued in Section 4.

2. RISK ANALYSIS BASICS

2.1 THE CONCEPTS OF RISK

The word "risk" is used by different people with different meanings. In the vocabulary of the general public, the word "risk" indicates a measure of the dangerousness of a situation or an activity; that is, it is a part of the judgment that people have when they think of activities that are dangerous in some respect, like living next to a chemical plant, driving a motorcycle, flying, etc. (Vrijling, et al., 1995). Cohrssen and Covello (1989) define risk as the possibility of suffering harm from a hazard. Other definitions for risk, including subjective risk and objective risk, can be found in a series of collected papers on risk analysis, risk management and risk communication (Glickman and Gough, 1990).

In one quantitative representation, risk is defined as the probability of an event occurring which has a detrimental effect on either people or property. In other cases, risk represents the frequency of occurrence of an "average magnitude" detrimental effect (of all possible magnitudes of detrimental effects). The problem with defining risk by the frequency of occurrence of an "average magnitude" event is that it is easy to miss considering large consequence events and determining whether they occur frequently, rarely or extremely rarely. Technical risk analyses which are used to understand (and, therefore, develop approaches to reducing) the risks in an activity tend to evaluate the frequency of occurrence of events of different magnitude. There are in general two approaches, namely, (1) subjective assessment procedure based on experience, and (2) quantitative evaluation using historical statistical information.

The first approach, which is extensively used as a tool in risk screening studies is based on the categorization of the probabilities of occurrence of "important," high level, events in the system into several distinct, albeit subjective, categories. Similarly, the consequences of occurrence of these high level events are expressed in distinct, but subjective, magnitude categories. This approach is based on the risk methodology used by the U.S. Department of Defense and is indicated in MIL-STD 882D. Figure 1 shows the Risk Assessment Matrix consisting of five event occurrence frequency categories and four hazard categories. Broad definitions are indicated in the MIL-STD for the various hazard probability levels and hazard severity categories. For example, the "frequent" category is defined as an event that is "likely to occur frequently" whereas the "improbable" event is described as one which is "so unlikely, it can be assumed that the occurrence may not be experienced." A "catastrophic" hazard is defined as one in which "death, system loss, or severe environmental damage" can be assumed to occur.

Frequency	Hazard Category			
	1–Catastrophic	2–Critical	3–Marginal	4-Negligible
A – Frequent	1A	2A	3A	4A
B – Probable	1B	2B	3B	4B
C – Occasional	1C	2C	3C	4C
D – Remote	1D	2D	3D	4D
E – Improbable	1E	2E	3E	4E

Acceptability Criteria

1A, 1B, 1C, 2A, 2B, 3A	Unacceptable
1D, 2C, 2D, 3B, 3C	Undesirable (Management decision)
1E, 2E, 3D, 3E, 4A, 4B	Acceptable with review by management
4C, 4D, 4E	Acceptable without review

Source: MIL-STD 882D, Appendix A.

Figure 1. Risk Assessment Matrix

In the more technical approach to determining the risks from a system, historical- or experience-based statistical data for failures of components or systems are used to determine the numerical probabilities of system failures. For each type of failure, the consequence is determined. Typically, the risk is represented graphically in the form of a "Risk Profile" which indicates the magnitude of consequence from the unwanted event on the X-axis and the annual probability of exceedance (of consequence of a given magnitude) on the Y-axis. Such a profile can then be studied to see the effect of various factors which influence either the probabilities of occurrence of events of different magnitude or the magnitude of the consequence itself. Consequences of unwanted events (accidents) are expressed as a number indicating either fatalities, injuries, or in an economic equivalent measure (of fatalities or injuries), when the effects on people are considered. Other measures of consequences include economic value of property damage, lost productivity time, opportunity costs, etc. In the case of risk analyses related to railroad operations, injury and fatality to people as well as property damage measures are used to evaluate the consequences.

In performing a risk study, it is essential to keep in sight the "normal or baseline" risks to which individuals and society as a whole are subject in a technological world. Such a perspective provides a "yard stick" by which the acceptability of the risks posed by a system or an enterprise can be compared with the "baseline" risks. The next section illustrates some of the baseline risk values for a number of activities undertaken by people.

2.2 RISK MAGNITUDES

All activities undertaken by human beings involve some degree of risk; that is, there is no activity which does not have a potential for an outcome that is unwanted or undesirable. However, not all activities pose the same degree of risk. A number of researchers have documented the "normal" risks posed by different activities. Table 1 shows a sample of these risks expressed as chances of occurrence in a year in a whole population. These 'actuarial' risks are expressed in number of fatalities per 100,000 persons in the named group population from all normal causes. It is seen that on the average the "risk of dying from living" in the U.S. is about 1 in 100 (or 10^{-2}) per year.

Voluntary and Involuntary Risks: Chauncey Starr (1969) suggested that societal activities can be categorized into those in which an individual participates on a "voluntary" basis and those in which the participation is "involuntary," imposed by the society in which the individual lives. In the case of voluntary activities, individuals use their own value system to evaluate their experiences and weigh these against the benefits they receive. Starr argues that in the case of voluntary risk taking, individuals optimize their choices in a relatively short time frame. In general, people undertake voluntarily activities that are perceived to be beneficial to them.

Involuntary activities differ in that the criteria and options are determined not only by the individuals affected but by an external controlling body (e.g., government agency, political entity, a leadership group, or "opinion makers"). According to Starr's research, society in general accepts voluntary risks which are several orders of magnitude higher than the risks when imposed by others; risks that society is forced to accept due to decisions made by someone else. Starr concludes that the public is willing to accept "voluntary" risks which are about 1000 times greater than "involuntary" risks (risk acceptance is proportional to the cube of the benefits) and the social acceptance of risk is directly influenced by the public awareness of the benefits of an activity. The research of Slovic, et al. (1979) indicates that factors such as the "dread factor" (botulism, tornadoes, flood, nuclear radiation exposure, etc.), repeated exposure to information on certain types of hazards (news items on homicide, motor vehicle accidents), and complexity of the technology (nuclear power, heart surgery) influence the perception of risk in the general population, especially about the involuntary risk. It is interesting to note from the Slovic study that the public perception of risk in rail travel is close to the actual risk as determined by technical experts.

Individual versus Societal Risks: In a quantitative evaluation of the risks, different perspectives are considered. These include the "individual risk," "societal risk," risk to employees, owners and operators of a system, etc. Individual risk is defined as "the frequency at which an identified individual may be expected to sustain a given level of harm from the realization of specified hazards" (Vrijling, et al., 1995). Table 1 shows individual risks in the U.S. population from a variety of activities. The meaning of the numbers in this table is best illustrated by an example: the overall risk of dying each year from all causes (by just being a resident of the U.S.) is one in a hundred. The risk of dying in any given year by being a firefighter fighting fires is 1 in 1250 or 8×10^{-4}. That is, on the average, 80 firefighters suffer fatalities annually per 100,000 firefighters. This risk is in addition to the "basic risk" of one in a hundred. Therefore, the firefighter risk of 1 in 1250 should be viewed as a marginal increase in risk due to the profession. Table 2 shows the individual fatality and injury risks by profession in the U.S.; i.e., the risk of fatality or injury for an individual due to profession-related accidents within a specified population group of the same type of professionals. It is seen that the injury risks are about two orders of magnitude higher than the fatality risks. Similarly, the individual risk from railroad operations to passengers, railroad workers and third parties are indicated in Table 3. As can be seen from this table, the fatality risk to the train crew is of the same order of magnitude as the risk in other similar professions. On the other hand, the annual risk to an individual using rail travel is quite small compared to an individual railroad crew member.

Table 1. Actuarial (Fatality) Risks in the U.S. by Activity

	Annual Risk expressed as		
	Fatalities per 100,000 population	Annual Probability	
Activity		$= 10^{-4}$ x	1 in
Overall population; All risks	1,000	100.0	100
Age 45-54: All risks	584	58.4	171
Smoker (one or more packs per day)	300	30.0	333
Age 35-44; All risks	229	22.9	437
Skydiving	200	20.0	500
Age 25-34; All risks	137	13.7	730
Firefighter	80	8.0	1,250
Police Officer	22	2.2	4,545
Automobile Accident	21	2.1	4,762
Appendectomy Operation	20	2.0	5,000
Woman giving birth to a baby	11	1.1	9,090
Hit by a drunk driver	5	0.5	20,000
In home fires	3	0.3	33,333
Pedestrian struck by vehicle	2	0.2	50,000
Airline Crash (10 trips)	1	0.1	100,000
Lightning impact	0.05	0.005	2,000,000

Source: Breyer (1992)

Societal Risk: This is the risk to the overall population defined as "frequency of occurrence of events causing a specified level of harm to a specified number of persons in a given population from the realization of all hazards." For example, the societal risk from railroad accidents involving the release of poisonous materials from a train consist could be evaluated as the frequency (number of events per year) of exposing, say, greater than 100 persons in a population along the rail corridor to a toxic concentration level of 500 ppm or more. In general, the societal risk is larger than the corresponding individual risk because of the cumulative effect of the potential for subjecting to harm many individuals (for the same level of exposure). Regulatory agencies, in general, are concerned with greatly reducing societal risks from the regulated activity.

Table 2. Occupational (Individual) Risk for a U.S. Worker (1995 Data)

Profession	Annual Probability of			
	Fatality $= 10^{-4}$ x	1 in	Lost-workday Injury $= 10^{-2}$ x	1 in
Agriculture, Forestry, Fishing	4.82	2,075	4.2	24
Taxis, School Buses	2.92	3,425	8.0	13
Water Transportation	2.92	3,425	4.8	21
Mining	2.68	3,731	3.8	26
Trucking & Warehousing	2.46	4,065	6.9	14
Construction	2.06	4,854	5	21
Railroads	1.28	7,813	3.2	31
Utilities	1.01	9,901	3.5	29
Aviation	0.97	10,309	7.9	13
Manufacturing	0.38	26,316	4.6	22
Wholesale and Retail	0.34	29,412	3.1	32
Services	0.24	41,667	2.7	37
Finance, Insurance, Real Estate	0.19	52,632	0.9	111
Communications	0.18	55,556	1.5	67

Source: Based on the data of Bureau of Labor Statistics (1996 a, b)

Table 3. Railroad Operations Related Fatality Risks

Railroad Related Activity	Annual Probability $= 10^{-4}$ x	1 in
Train crew	2.86	3,497
All railroad employees	1.67	5,988
Crossing highway crossing (with passive warning devices) twice a day	0.054	185,185
Business day commuting by train, 20 miles each day	0.047(1)	212,766
Trespassing or by-standing	0.019(2)	526,316
Crossing highway crossing (with active warning devices) twice a day	0.013	769,231

Source: Savage (1998)

(1) Assuming the rate of railroad passenger fatality is 0.81 per billion passenger miles.

(2) Risk is based on per head of population at large.

2.3 RISK DETERMINATION

The determination of the risks from an activity involves a thorough understanding of the features of the activity, identification of the various scenarios which can cause detrimental effects on people and/or property, and estimation of the likelihood (or frequency) of occurrence of the various scenarios and the evaluation of the magnitude of the consequences under each scenario. While the principles enunciated in the previous sentence are simple, a number of difficulties arise when actually performing the risk calculations.

Before a risk assessment is initiated, it is necessary to make certain *a priori* decisions. These include what may be called the first-level decisions such as (1) at what level of the system should the failure frequencies be aggregated?; and (2) what measure should be used for determining the consequences? The level of aggregation of the system failure or accident frequencies will depend on the accuracy of the results needed and the complexity of the methodology used.

In the case of railroad operations, broad categories of accident scenarios such as collisions, derailments and hazards that are independent of rail operations (certain types of fires, terrorism) can be considered and their overall frequency of occurrence calculated. The second-level detail for such aggregation will be the development of individual sub-scenarios that lead to the first-level failures. One can go into further complexity in the determination of the frequency of failures by considering the individual component failures that can lead to the assumed scenarios. For example, Bing (1993) has considered 'collisions' as the only type of accidents in his analysis of risks from high speed trains; however, different categories of collisions (between a High-Speed Train (HST) and other types of trains, HST-to-obstruction, HST-to-bystander, etc) are considered. The rates of collision are estimated from historical data on train collisions. This approach is contrasted with the approach by Kokkins, et al. (1999) where very detailed information on the track and train parameters as well as the signal and operational details are considered, mile by mile, to arrive at the overall frequency of collisions (of different categories) and train derailments. Larech, et al. (1998) consider details of various metrics (simultaneous presence colliding trains, failure of signals, delayed action by train engineer, failure of brakes and stopping distance, etc.) in estimating the frequency of collisions. In effect, there is a spectrum of approaches to determining the frequencies of system failures including a combination of historical accident data in similar systems, extrapolation to new systems, component failure data, engineering judgment, and in some cases, educated guesses.

Similarly, the consequence measure also needs to be defined before the overall risk from a system can be determined. The consequence measures generally used includes fatalities, bodily injury (level of injury can also be specified such as minor, in situ first aid, hospitalization, etc.), exposure to certain levels of harm (especially in toxic chemical hazard determination), economic equivalent values for death and injury, property damage, environmental damage, etc. In general, the measures used in rail passenger transportation for consequence measurements are fatalities, injuries (and/or their economic equivalents), direct property damage, and opportunity cost of system failures.

In the performance of risk assessment, it is also important to define *a priori* whether one is interested in the immediate consequences ("acute hazards") or long term consequences ("chronic hazards"). The difference in the two types of consequences lies in the time frame for the effect of the system failure to manifest itself. In the case of acute hazard, the effect is immediate (in a time frame of minutes, hours, or at best, a day) whereas the effects of a chronic hazard can manifest a long time after exposure (months to years). For example, the release of a chemical from a transportation accident resulting in a fire can pose an "acute" hazard since the effects of the fire are felt in a very short time (such as burning of the property exposed, burn injuries to people, etc.). Other examples of "acute" hazards include exposure to toxic and poisonous chemicals, explosion-caused blast wave, impact by metal fragments and other debris from an accident, crushing of vehicles due to collisions, etc. Chronic hazards arise, long after the accident occurs, due to prolonged and continuous exposure of people to low concentrations of chemicals (because of slow migration and/or emission of chemicals in the atmosphere or in the ground water).

Examples of chronic hazards include those resulting from low concentration vapor exposure, carcinogens ingested from a contaminated water supply, lead poisoning, exposure to low level concentration of chemicals at job sites, etc. In the case of the evaluation of HST risks to passengers and people external to the train, only immediate and acute hazards are considered.

2.4 RISK ACCEPTABILITY

The annual fatality values for an average year estimated by the general population for a number of "familiar" technologies is generally less than both historical fatality data and those estimated by technical experts, which researchers use in place of hard-to-find fatality data or in comparison of actual numbers. This seems to be so because of the infrequent occurrence of a large number of deaths in these technologies occurring in a single incident. People have short memories for new items reporting fatalities (especially if the numbers are relatively small). In addition, the geographically distributed nature of the incidents also contributes to this underestimate. Ordinary people do not keep count of the cumulative number of fatalities. This is, however, in contrast to high profile reporting of air disasters with multiple fatalities which tend to exaggerate (in the minds of the public) the annual number of deaths from aviation accidents. That is, the perception of risk from a specific technology can be completely, and in some cases orders of magnitude, different from historical risks. The number of fatalities for an average year in many common technologies estimated by technical experts, used by the study authors as a marker for actual numbers, as well as the general public is shown in Table 4. Also shown in this table are the factors (Disaster Factor) by which the public seems to enhance the number of predicted fatalities if asked to consider it a particularly accident-prone (and worst accident occurrence) year. This factor also indicates the "disaster potential" of the particular technology as perceived by the public. The nuclear plant is a case in point. While in the normal operational year, the public tends to underestimate the number of fatalities; it significantly overestimates the fatality numbers if the year in question is perceived as a more accident-prone year.

People are generally very reluctant to be subjected to any additional risk without being assured that the benefits are substantial. The general population seems to equate involuntary risk with more than actuarial fatality values; in fact, such qualitative factors as the immediacy of effect, knowledge about and newness of the technology, chronic or catastrophic potential, the dread factor, and the severity of consequences. Of all the above parameters, the disaster potential of the technology seems to influence the perceived risk versus the actual risk based on historical data on fatalities (Slovic, et al., 1979). Table 4 shows the perceived disaster potential (and hence the degree of perceived risk) from different technologies and activities. Therefore, in an assessment of risk from a technology, it is not enough merely to calculate the "technical" consequence/risk based on actuarial data and/or physical models, but to consider the acceptability factor (exemplified by the "disaster factor") such as the ones in Table 4.

Starr (1969) has indicated that involuntary risk to an individual posed by a technology must be at least 1000 times smaller than the risk that individual may undertake voluntarily. Vrijling, et al. (1995) suggests that the acceptable involuntary individual risk should be less than 1 percent of the lowest individual risk from all normal activities in a population. Based on Dutch actuarial fatality data for 6- to 20-year-old persons, they conclude that any new technological activity should not pose an annual fatality risk to an individual exceeding a probability of 10^{-6}. In fact, Vrijling, et al.

introduce the concept of an involuntary factor for acceptable risk defined by the following equation.

$$\textbf{Acceptable individual involuntary risk /year} < \beta \times 10^{-4} \qquad (1)$$

where β is a factor that represents the degree of involuntariness in the activity. The value of β varies from an upper value of 10 for mountaineering undertaken by the individual by his own volition to a low of 0.01 for a chemical plant in whose siting decision the individual has no significant say.

The British Health and Safety Executive (HSE) has promulgated guidelines on acceptable individual risks from technological activities (HSE, 1989). The individual risks are classified into three categories, namely, (1) "negligible risks" which have probabilities of the same order of magnitude as an individual being struck by lightning, (2) "as low as reasonably practicable or ALARP risk" which is ill-defined quantitatively, and (3) "intolerable risks" which are so large that they are unacceptable and action to mitigate these risks should be taken without regard to the financial consequences. Vrjling, et al. indicate that the ALARP criterion of HSE is equivalent to the criterion in equation 1.

In regard to risk acceptability in the passenger transport by rail, Savage (1998) argues that individual risk posed due to rail accidents can be considered "intolerable" if employees and passengers (who get some benefit from the operations) face a risk of more than 1 in 10,000 (or 10^{-4}/year), highway crossing users more than 1 in 100,000 (i.e., 10^{-5}/year) and third parties more than 1 in 1,000,000 (10^{-6}/year). This is in keeping with the recommendations of Vrjling, et al. as indicated in equation 1. Table 5 shows a comparison of the HSE/British Rail guidelines related to tolerable risks and the British and U.S. experience.

Table 4. Perceived U.S. Fatality Values and Disaster Factors

Activity or Technology	Annual Fatality Estimates by		Disaster Factor*
	Technical Analysts	Non-Technical People	
Smoking	150,000	6,900	1.9
Alcoholic Beverages	100,000	12,000	1.9
Motor Vehicles	50,000	28,000	1.6
Handguns	17,000	3,000	2.6
Electric Power	14,000	660	1.9
Motorcycles	3,000	1,600	1.8
Swimming	3,000	930	1.6
Surgery	2,800	2,500	1.5
X-Rays	2,300	90	2.7
Railroads	1,950	190	3.2
General (private)Aviation	1,300	550	2.8
Large Construction	1,000	400	2.1
Bicycles	1,000	910	1.8
Hunting	800	380	1.8
Home Appliances	200	200	1.6
Fire Fighting	195	220	2.3
Police Work	160	460	2.1
Commercial Aviation	130	280	3.0
Nuclear Power	100	20	107.1
Mountain Climbing	30	50	1.9
Power Mowers	24	40	1.6
Skiing	18	55	1.9
Vaccinations	10	65	2.1

Source: Slovic, et al. (1979)
*See text on page 11.

Table 5. Intolerable Individual Fatality Risk† from Rail Accidents

(Individual risk = Reciprocal of the number in the table)

Individual Exposed		British Guideline	Actual Experience	
			British Rail	US Railroads
Railroad Employees		10,000	18,500	6,000
Passenger	per mile	50,000,000	1,337,000,000	1,370,000,000
	per year*	10,000	250,000	215,000
Grade Crossing users		100,000	--	185,000
Trespassers		--	500,000	500,000
Third Parties		1,000,000	25,000,000	6,000,000

Source: Savage (1998)
† Risk numbers are annual risks unless otherwise indicated
* Estimate based on 20-mile commute per work day per person

The acceptable societal risk, as discussed earlier, is always greater than the acceptable individual risk. This is because the societal risk is, in general, the aggregate of the risk posed to each and every individual potentially exposed to the harmful effects of an accident/incident. A regulatory agency evaluating the siting of a new technology may require that the proposed activity not pose a risk greater than the involuntary individual risk (as indicated above) to each individual potentially affected by the new activity. That is, it can require that the technological activity pose a societal risk not exceeding a set threshold. Vrjling, et al. propose that for any new activity to be acceptable, it should satisfy the following "Societal Fatality Risk" criterion:

$$\textbf{Societal Fatality Risk (i.e., expected fatalities/year)} < \beta \times 10^{-5} \times \textbf{Size of National Population} \quad (2)$$

The application of the above criterion to the U.S. leads to a condition that no "project" is acceptable where the U.S.-wide annual fatality risk exceeds 25.[7]

While the above equation provides an overall threshold of acceptability from an expected value perspective, it may not be sufficient when a spectrum of accident scenarios can occur resulting in a wide variation in the number of potential fatalities. In such a case, Vrjling, et al. propose the following criterion of acceptability for the value of probability of exceedance:

$$F_N < 10^{-3}/N^2 \qquad \text{for} \quad N >= 10 \quad (3)$$

where, F_N represents the annual frequency of exceeding a consequence of N fatalities. As can be seen from this equation (which is the result of a political process to site liquified petroleum gas (LPG) stations in Holland), the F_N versus N curve on a log-log scale has a -2 slope.

Mathematical models have been developed to assess the risks in passenger railroad operations (with emphasis on high-speed ground transportation systems) and freight railroad operations (primarily hazardous materials). These models, in general are based on the risk analysis concepts discussed in this chapter. The models are reviewed in Section 3.

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[7] This is based on a U.S. population of 250 million and β=0.01 for the involuntary risk.

3. RAIL TRANSPORTATION RISK MODELS

This section reviews the research efforts conducted in the past decade related to the evaluation of risks in the transportation of passengers in the U.S. and other (foreign) railroad systems. The focus of the review is on risk models related to passenger transport systems. First, the research efforts sponsored by FRA and conducted by the Volpe Center and its contractors are discussed. Also reviewed are other research efforts related to railroad risks and risks related to high-speed trains conducted by the Center for Transportation Studies at Massachusetts Institute of Technology (MIT) and other institutions. Other relevant research (sponsored by the FRA) such as the analysis of risks of rail transportation hazardous materials on U.S. railroad system, fire safety in passenger cars, etc. are also reviewed, briefly. Where possible, the influence of research results on the corresponding regulations (or regulatory efforts) are also discussed.

The risk analysis and other research efforts are reviewed from the perspective of their research objectives, principal approach, model details, and results. Also indicated are the discussions on the research results and summary of the findings.

3.1 FRA-SPONSORED PASSENGER RAIL SYSTEM-RELATED RESEARCH

The research of the risks in passenger rail systems has been conducted at three distinct levels of complexity. The first level is the collection of data on railroad accidents from both U.S. and foreign operations for low-speed and high-speed trains and using these data to determine what the specifications should be for the various subsystem performance in a passenger rail system. The focus of the first level of research is the development of simple risk analysis approaches useful for the generation of performance specifications. In the second level, screening type of risk analysis studies have been conducted. In the third level, detailed operational conditions, signal systems and vehicle dynamics are taken into account to calculate overall risks in specific passenger system corridors with other traffic on the shared rights-of-way (ROW). The FRA also has funded studies related to the engineering design and cost analysis of different types of fixed guideway systems for passenger rail systems.

3.1.1 Collision Avoidance and Accident Survivability Study

Objectives: This FRA-sponsored research conducted by Arthur D. Little, Inc. (Bing, 1993a) was concerned with developing potential safety guidelines and specifications for railroad system collision avoidance and accident survivability.

Approach and Results: The work in this project has focused on three areas of concern related to passenger rail systems. In the first part, the past rail accidents in the U.S. and in other foreign countries involving high-speed trains are reviewed and, based on these, collision scenarios are developed. In the second part, possible foreign and U.S. safety regulations governing the operation of a passenger train are reviewed. The third part reviews some approaches and guidelines for avoiding collisions and surviving such accidents. A risk analysis approach is used to discuss the degree and level of safety that should be provided in a passenger rail system.

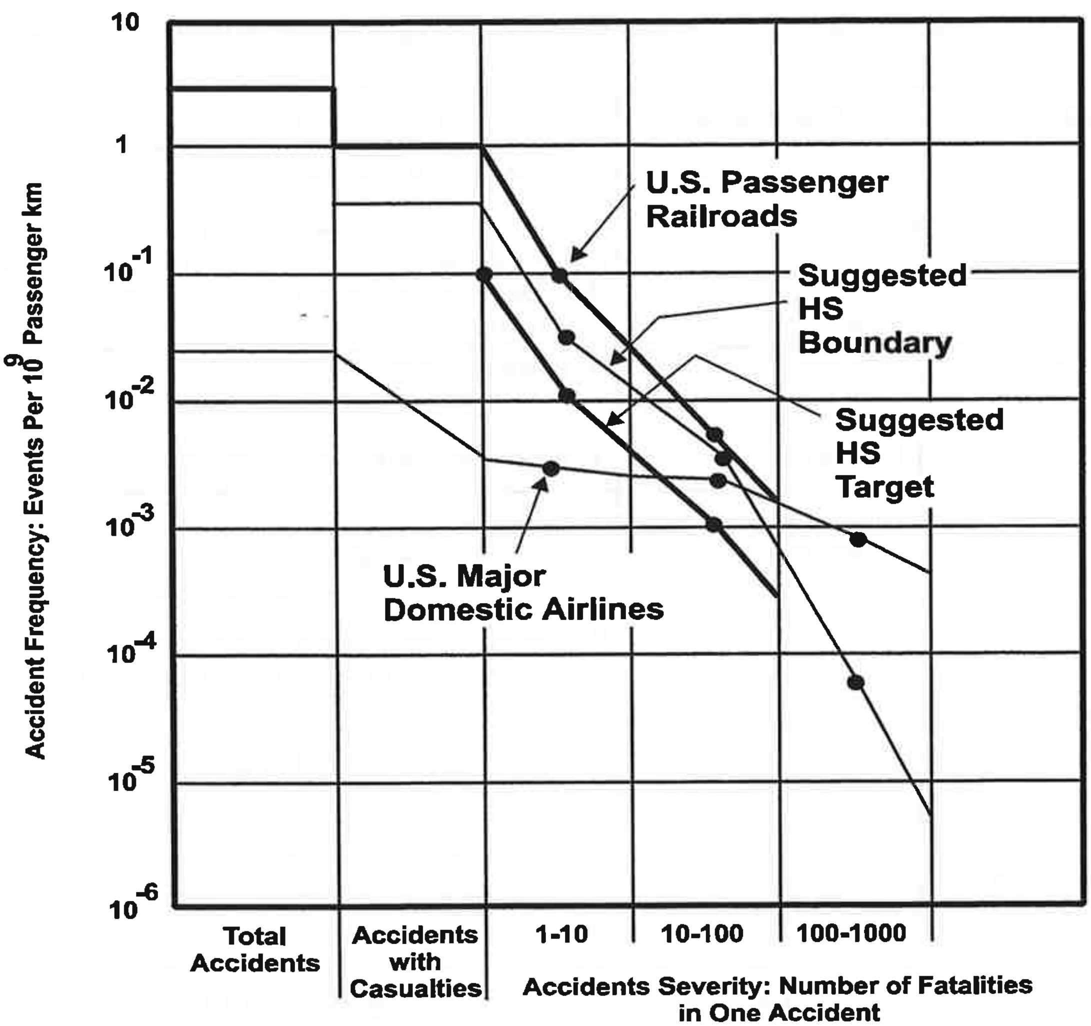
Four broad categories of collision/derailment accident scenarios are discussed such as (1) collision with similar trains at different speeds; (2) collisions with obstructions such as at grade crossings, wayside equipment, debris on the guideway, etc.; (3) collision with dissimilar trains, such as freight trains; and (4) single train events in which the train derails due to track defects, rolling stock defect, incorrect switch positions, etc. Detailed discussions are provided on the causes of various collision scenarios; their occurrence statistics from historical accident data, and the magnitude of the energies dissipated in the collisions. Table 6 shows the relationship between energy dissipated in a train collision accident and the severity of damage or casualty that can result in rail vehicles designed to U.S. structural requirement specifications.

Table 6. Train Collision Energy Dissipation and Accident Severity

Energy Dissipated in Train Collision MegaJoule (MJ)	Accident Severity
Less than 10	Minor damage to the cab and vehicle structures; minor injuries.
10 to 60	Crushing of vehicle ends; fatalities among control cab occupants possible; vehicles stay upright and in line; numerous minor/moderate injuries.
60 to 120	Severe damage to colliding vehicles at ends of train; significant risk of fatalities among end vehicle occupants; numerous minor/moderate injuries.
Over 120	Severe damage to two or more vehicles in each train possible; significant risk of high number of fatalities; numerous minor/moderate injuries.

Source: Bing (1993a) $1\ MJ = 7x10^5$ ft-lb

This research reviewed the concept of "equivalent safety" for a new system. The concept is based on the requirement that any new system should provide a safety record better than or, at the very least, equal to the safety of the system it is replacing. This dictum requires that passenger rail system safety should meet or exceed that of the current safety record of passenger trains in the U.S. The key question is how one defines the term "safety." Bing argues that the best approach is to use the "risk profile" of current rail operations and air traffic transportation technologies as a yardstick and require the safety of a passenger rail system, as described by risk profiles, to be within the acceptable norm. Based on a review of passenger rail accidents in the period 1985-1987 and the results from the National Transportation Safety Board (NTSB) investigation of major accidents for 20 years and air accident statistics, Bing has provided a risk profile for each of low-speed passenger trains and commercial aviation operations in the U.S. The potential risk profile for a passenger rail system is also provided based on the argument of societal acceptability of risks in high-speed train transportation being closer to airline operations. These risk profiles are shown in Figure 2.



Source: Bing (1993a)
(Units left in km per original source document)

Figure 2. Risk Profiles for Passenger Railroad and Airline Operations in the U.S. and Suggested Risk Profile for a High-Speed Rail System Operation

Based on the above work and review of past accident statistics, Bing (1993b) has recommended a number of performance specifications for passenger rail systems in terms of risk parameters. A summary of these recommended parameter values is shown in Table 7.

Table 7. Recommended Risk-based Specifications for a High-Speed Rail System

Risk Group	Description	Maximum Value Allowable
Vehicle Occupants	Passenger and crew individual risk	0.32 fatality per billion passenger miles.
Overall Accidents	Societal risk	Fatality risk profile indicated in Figure 2 of Bing (1993b). Accident probability per billion passenger m < 0.1 x $N^{-4/3}$ with N= # of fatalities.
Employees	Individual risk	4 per 100,000 employees.
Bystanders	Societal risk	1.6 fatality per 200 billion passenger miles.
Structure of high-speed rail and other trains	Collision at speeds of: 6.2 mph or less	No permanent structural damage to either train 0.2 g Longitudinal acceleration 0.3 g/s Rate of change of acceleration (jerk)
	31 mph	No crushing of seating space of passengers or crew. Deceleration less than to cause head injury to passengers.
Signaling & train control system	High-speed rail system operation in 80 - 125 mph and multiple unit or push-pull train with passengers in the leading vehicle	8×10^{-3} collisions per billion passenger miles for passengers in leading vehicle. 3.2×10^{-2} collisions per billion passenger miles for no passengers in the leading vehicle.
	High-speed rail system operation over 125 mph	Collision frequency not to exceed 0.8×10^{-2} collisions per billion passenger miles

Source: Bing (1993b)

Discussion: This study has indicated a reasonable way to include a number of operational and performance characteristics of a passenger rail system operation in a safe manner. Whether the recommended set of specifications for performance under different conditions are the best is not certain until a specific operational corridor is studied in detail and the overall risks in that corridor are assessed in terms of the proposed guidelines. Bing has interpreted the FRA's dictum of "equivalent safety" to mean the considerations of fatalities only as the criterion of risk. As will be pointed out, injuries may constitute a larger risk in train accidents. Conceptually, this approach can be easily modified to include additional risk indicators such as injuries.

There are some structural issues related to the metrics of parameters used. The individual risk rates for passengers in intercity and commuter trains are expressed in fatalities per billion passenger trips. These are, respectively, 0.56/billion passenger miles and 0.133/billion passenger trips. The employee risks are expressed in terms of the number of fatalities per 100,000 employees. There is a question as to whether the employee risks also should be expressed in terms of number of fatalities per train mile or per train operation. The use of bpm to express the bystander fatality rates is, in our opinion, an incorrect representation of the risk to the bystander.

A bystander is not affected by how many passengers are on the train, but only on the number of trains per year and, perhaps, on the number of grade crossings or opportunities for intruding onto the guideway, per unit distance. Therefore, it may be more accurate to express all individual risk quantities in terms of passenger train miles.

An important addition to this study would be some examples of how the risk in a specific high-speed rail system corridor can be calculated using the proposed specifications and how the risk compares with the normal railroad operations.

3.1.2 Study for Shared Right-of-Way: Safety Issues

Objectives: This study was sponsored by the FRA and conducted by Battelle Memorial Institute with a view to analyzing the threats (as expressed in objective measures of risk) to the safety of passengers, integrity of equipment in a high-speed rail system and the other transportation vehicles arising from a high-speed rail system sharing an ROW with other transportation modes.

Approach and Results: The application of risk assessment approach of MIL-STD 882D to screening the risks in Maglev systems and high-speed rail systems that can use the existing ROW has been made by Hadden, et al. (1992). This effort involved characterizing a baseline high-speed system using some of the characteristics of currently operating a high-speed rail system and corridors as well as prototype systems in foreign countries. The features of potential ROW users such as low-speed trains, highway vehicles, waterway, and pipeline are taken into consideration. The risks, in terms of the MIL-STD 882D parameters, have been evaluated for several accident scenarios with and without mitigation techniques for a 400-mile, high-speed rail corridor potentially carrying 7 million passengers per year and sharing the ROW with other modes.

The risk analysis that was performed is based on first identifying the "safety issues" and then determining the various scenarios that can lead to the safety issues. A "safety issue" is defined as the principal undesirable event that has the potential for passenger or employee injury, property damage, or systems loss in either of the transport modes associated with the shared ROW. Based on this definition, six safety issues are identified, namely, (1) physical infringement of vehicles or structures from one use onto another, (2) electromagnetic field (EMF) effects, (3) dynamic interference between users, (4) infringement of operating envelope involving common trackage for high-speed rail (only), (5) transportation of hazardous materials (hazmat) by the other user, and (6) accessibility of high-speed rail vehicles or guideways for inspection, emergency access, evacuation, and trespassers.

In order to facilitate the mapping of the risk results onto the MIL-STD 882D risk parameters, Hadden et al. (1992) have defined the equivalence of quantitative frequency measures obtained from accident occurrence data of current non-high-speed and high-speed rail operations to the MIL-STD frequency categories. This equivalence is indicated in Table 8.

Table 8. Equivalence Between Quantitative Accident Frequency and MIL-STD 882D Frequency Categories

MIL-STD 882D Occurrence Frequency			Quantitative Railroad Accident Frequency (Events/Year)	
Levels	**Categories**	**Generic Description**	**Low Range**	**High Range**
A	Frequent	Continuously experienced	1	-
B	Probable	Will occur frequently	0.1	1
C	Occasional	Will occur several times in the life of the system	0.01	0.1
D	Remote	Unlikely, but can be reasonably expected to occur	0.001	0.01
E	Improbable	Unlikely to occur, but possible	0	0.001

Source: Hadden, et al. (1992)

A key assumption made in the risk analysis is that the derailment probability of a high-speed rail vehicle from its track or guideway is remote (once in 100 years to once in 1000 years). Other mode failure frequencies are based on actual experience and are indicated in Table 9.

Table 9. Other Mode Accident Frequencies

Mode	Frequency	Remarks
High Voltage Transmission Lines	10^{-1}/year/mile	
Highways	9.3×10^{-2}/year/mile	
Railroads	4.2×10^{-3}/year/mile	Excludes yards, sidings and derailments below 10 km/hr
Waterways	10^{-1}/year	Flooding of urban areas
Pipelines	4.6×10^{-4}/year/mile	Based on the data of bursting of natural gas pipelines

Source: Hadden, et al. (1992)

Based on the above and several other assumptions related to the occurrence of the particular types of accident scenarios, Hadden et al. have identified 16 different high-speed rail (HSR) and maglev interactions with each of the above five modes of transportation which share an ROW. An example corridor was considered with a length of 400 miles, of which 200 miles is on a shared ROW, and carrying 7 million passengers/year. The accident frequencies and the resulting casualties are determined on the MIL-STD matrix parameters. It is seen that in all cases studied, the consequence score of an accident is 'catastrophic' (except in the one case of a pipeline burst) and the frequency scores range from 'probable' to 'improbable' before any mitigation approaches are considered. Several mitigation techniques are evaluated including (1) fail-safe signaling and control systems, (2) different structural designs of ROW, (3) separation of the shared ROW modes by distance, time and grade or elevation, (4) speed reduction, and (5) provision of sensors to detect other mode behavior, etc. The mitigation techniques are assumed to affect only the frequency of occurrence and not the consequence of an accident. Based on this assumption, the post mitigation scores indicate that 4 of the 16 scenarios are in the 'undesirable' range (all these involve the high-speed rail system interaction with other trains or highway vehicles).

Based on the screening risk assessment methodology used, Hadden, et al. conclude that the concept of shared ROW between a high-speed rail system and other modes is feasible and that mitigation methods must be used to reduce the frequency of occurrence of collision accidents.

Discussion: The approach taken by Hadden, et al. (1992) is a viable approach for an initial screening study. However, there are a number of limitations in using this type of methodology to determine the acceptability of a high-speed rail system on a particular ROW. For example, the authors have determined that almost all accidents result in 'catastrophic' casualties but at an 'improbable' frequency. First, the magnitude measure by which the 'catastrophic' casualties are determined is not explained. Second, a 'catastrophic' outcome from a high-speed rail system accident may not be socially acceptable even though an improbable - catastrophic combination outcome is indicated in the MIL-STD 882D to be acceptable. It is noted that MIL-STD 882D does not give any guidance on the issue of social acceptability nor does it define a 'system' rigorously.

In general, the estimates in this study of the frequency of occurrence of the accidents may be overly conservative. That is, conditional probabilities which tend to reduce the overall occurrence frequency have not been taken into account. As an example, consider the scenario of a highway truck straying into the high-speed rail system guideway; even with existing systems in place, there is a high probability that the truck will be cleared before the train hits it. The estimated frequency categories are based on a very high level of aggregation of events without taking into account current technologies in place which will mitigate accident occurrence. In other cases, however, the estimated frequency of occurrence of "rare" phenomena such as earthquakes and equipment-caused derailments may be underestimated. For example, the earthquake at Kobe, Japan, in 1996 and the recent accidents of the ICE in Germany and TGV in France are stark reminders that even "remote" frequency accidents can occur and should be taken into consideration in any decision making.

3.1.3 Case Study in Collision Safety

Objectives: This study was undertaken by Foster Miller, Inc., with the objective of developing a quantitative assessment of the overall collision safety of current U.S. intercity passenger train operations including high-speed hub-to-hub train operations. The quantitative assessment included many of the railroad operational features and structural description (for evaluating the collision performance) of rail passenger cars.

Approach and Results: The application of a detailed risk analysis process to a high-speed rail operation is indicated in DOT/FRA/ORD-97/08. In this study, an example corridor for a high-speed rail operation was designated with significant features of intercity passenger train operations. The study approach included the development of collision safety methodologies using the evaluated frequency and severity of passenger rail accidents on a defined composite rail corridor. The probabilities of occurrence of top-level accidents is determined by considering a series of event trees containing sub-events. The sub-event occurrences and their conditional probabilities and interactions are determined by a combination of long-term data, knowledge of real-time operational scenarios (especially interlocking movements), maintenance parameters, consist types, and the physical environment. Similarly, the severity or consequence of accidents were determined by evaluating the dynamic crushing response of the intercity passenger cars, characterizing the passenger dynamics and then calculating the passenger casualties under each accident condition.

Accident scenarios considered in this study constitute the highest level groupings of passenger rail accidents. These groupings include (1) collisions with secondary trains, (2) collisions with obstructions on the guideway, and (3) single train accidents. The word 'train' includes the regular passenger-carrying train as well as the maintenance-of-way equipment able to operate on the guideway. Different types of interlocking movements of a passenger train such as (a) normal interlocking movement, (b) following interlocking movement, (c) diverging interlocking movement, and (d) movement on track blocks, etc. are considered in the model. Also, other metrics of train operations are considered.

An example of a composite rail corridor consisting of a main corridor and a branch corridor is considered for a detailed assessment. The corridor features are described in terms of the length, and type of traffic (high-speed rail systems and other freight traffic as well as normal commuter train, slow speed traffic). The composite corridor considered has features of Amtrak's long distance service, Amtrak's denser corridor operations near a big city, and a high-speed rail corridor typical of recent proposals such as the Texas HSR or the Florida HSR initiatives. The example corridor is fully described in terms of signals, schedules, grade crossings, passenger and freight, train speed – all data provided on a link-wise basis. The frequency of potential accidents are evaluated for each segment of the corridor using the fault-tree approach and considering the conditional probabilities of sub-events.

Casualty calculations are also made for scenarios of collisions with heavy vehicles at grade crossings as a function of the train speed and head-on collisions with other trains at different relative train speeds. It is indicated that no comparison of the calculated fatalities could be made with actual experience because of the rare occurrences of train accidents resulting in passenger fatalities as well as the fact that the operating experience on high-speed rail systems in the U.S. is limited. However, the calculated results indicate that on the average, 25 fatalities can be expected for a grade crossing collision with a heavy vehicle (50 ton) and about 80 fatalities for the case of train-to-train collisions.

This continuing study has not developed, at present, the full risk profile for the corridor chosen nor has it attempted to determine the sensitivity of the various input parameter values, assumptions, and model approximations on the overall risk.

Discussion: The model presented is very detailed in that it attempts to take into consideration a large number of realistic features of the railroad operational and fixed parameters. The utility of such a model is dependent not only on the availability of the necessary infrastructure data but also detailed specifications on train schedules, passenger cars, guideway parameters, other ROW traffic, etc. While a complex model may give an impression of accuracy, the ultimate accuracy depends on the accuracy of the input data and the assumptions on the conditional probabilities of the failure of components and sub-systems used in the model. These are not easily discernible from the model indicated in this study.

The model has not been exercised to its ultimate result, i.e., in predicting the risk profile of probabilities of exceedance versus fatalities or other casualty measures. The results presented (collision probabilities, casualties at different speeds) do not provide a regulatory agency with relevant information as to which of the many factors that influence accidents and their severities are significant and what should be done to reduce the risk, overall. The study indicates that performing a single casualty calculation (crush model for car structural response) takes days of computer time. In such calculations, generally, parametric results are presented in the form of correlating (simple) equations; such a result is not provided in this study. Last but not the least, the results are not compared in the study with any other risk analysis results although individual component results (accident frequency, for example) have been compared with historical experience.

3.1.4 A Framework for Analysis of Risk and Train Control

Objectives: The study was conducted by a team at MIT with the objective of developing a parametric, model approach that has low resource requirements to evaluate the risks from train accidents on high-speed rail corridors and to examine how the risk varies with train control systems and strategies. The model should be comprehensive yet have the elegance of an analytical/statistical model. The second objective was to assess the impact of positive train control (PTC) systems on risk reduction using a parametric representation of a rail corridor.

Approach and Results: An analytical model and the results of application of the model to an example rail corridor are presented by Larech, et al. (1998). The model is applicable for evaluating the potential benefits (i.e., reduction in risk) from PTC systems. The scenarios of accidents considered include: (1) train collisions (head on, rear end, and maintenance way equipment), (2) derailments (over-speed in speed restricted zones, over-speed under diverging interlocking movement, train fault, track fault, and (3) collision with obstacles, primarily at grade crossings. The model in its present form handles all of the collision scenarios, and derailments due to track fault. An approach to considering the grade-crossing collision scenarios is also indicated.

The probability of occurrence of each accident scenario is determined by a two-step process. First, the occurrence of each accident scenario is related to a measure of the likelihood of a train being in that particular accident scenario ('scenario metric'). The metric for head-on collision is the number of meets and passes between trains on the segment of interest. These metrics are estimated using traffic and operational characteristics of the segment. Second, given a proper metric, each accident scenario is decomposed into a logical AND/OR sequence of events using the fault tree methodology. Probabilities of most individual events in the fault tree are empirically estimated drawing upon results of previous studies of human factors and train control system characteristics.

The consequences of accidents are expressed in societal cost equivalent value for fatalities and injuries. The expected monetary value of the consequence is expressed by the equation:

$$\mathbf{E} = \mathbf{2.7 \times 10^6 \times E\ (fatality) + 10^5 \times E\ (injury)} \qquad (4)$$

where, E is the expected value for the consequence in \$, E (fatality) is the expected number of fatalities and E (injury) is the expected number of injuries resulting from the accident.

The number of expected fatalities and injuries in an accident are related to the speed of the train and the location of the passenger car from the leading end. The relationship between the fatality-to-casualty ratio (FCR) which is the ratio of the number of fatalities to the number of fatalities and injuries in any car is related to that of the lead car in the form of an exponentially decreasing function with distance from the lead car. The relationship between the fraction of the people in a car that suffer casualty and the train speed is obtained from the computational results presented in DOT/FRA/ORD-97/08 with appropriate adjustments of the functional parameters with the type of the curve, gradient, whether the accident occurred in a tunnel or on a bridge. The equations and correlation parameter values are indicated in the report.

The head-on collision risk is calculated by first determining the probability of two trains being on the same track (within a blocked section) by knowing the schedule and departure frequency of trains. This probability is then multiplied by the conditional probability that a collision occurs after discovering that the trains are on the collision path. That is, a determination is made on whether the trains collide or not based on the time of deployment of the brakes, effectiveness of the brakes, initial train speeds, and the initial separation distance between the trains. The effectiveness of the presence of PTC is factored in the form of a lag time T (i.e., the time between the overrun of the home signal by the first train and the start of emergency braking by the second train). The value of T is assumed to be 60 seconds for an Automatic Block Signaling (ABS) with data link by radio (to a central control), 30 seconds, 15 seconds, and 0 seconds, respectively, for PTC1, PTC2 and PTC3. In order to calculate the closing impact speed for a single instance of a collision, the following variables are considered: (1) separation between trains (i.e., in which of the B blocks between interlockings the secondary train is located), (2) the block before the home signal at which the primary train commences braking, and (3) the braking state of the primary train. The authors indicate that there are 15xB different cases for which the probability of collision need to be determined. Assuming a uniform distribution of the location of the secondary train, the expected value of the risks per meet is then obtained. Multiplying this expected value per meet by the number of meets per year yields a measure of the annual head-on collision risk.

Similar analysis of the probability of rear-end collision risk is also developed in this study. The collision risk with the maintenance-of-way (MOW) equipment is determined by calculating the number of work gangs that may be present in a given length of track between a pair of interlockings. The number of encounters with such MOW equipment is calculated and the formula developed for the head-on collision is used with the assumption that the MOW equipment represent a "stationary" secondary train.

The derailment probability (or alternately the expected value of the number of derailments per year per unit length of track) due to track fault is calculated by considering the number of times a train exceeds the critical derailment velocity when traveling at a speed of V_0 and encounters a restrictive signal due to a broken rail located at a distance d and instituting a braking action with a time lag T. In addition, the expected value of the severity due to derailment is also calculated by noting the distribution of derailment speeds for given initial speed and the lag time for initiation of emergency braking. The presence of PTC is taken into consideration by setting the time lag for emergency brake application T to zero.

The study report has provided example results for a hypothetical passenger service corridor of 62.5 miles in length with five passenger trains per day, double track operation, 4,920 feet uniform block length. Sensitivity analysis of the dependence of the head-on collision accident frequency with speed, collision risk (in dollars) with speed, freight traffic volume, passenger train traffic volume, and risk sensitivity to length of blocks are evaluated under conditions of ABS, and three different levels of PTC. The results show trends that can be intuitively estimated with respect to the direction of change of accident frequency and/or risk with increase in speed (risk increases exponentially with speed), increase in train traffic, etc. The quantitative values are indicated in the report in a series of graphs. It is noted that the provision of PTC Level 3 results in the lowest risk for each parameter considered. The degree of reduction compared to risk under ABS is generally between one to two orders of magnitude.

The model developed has also been applied to evaluating the overall risk under ABS and PTC for a corridor. The features of the corridor include a 25-mile segment representing a suburban area rail operation with a mix of freight, commuter and frequent passenger service. The next segment consists of a 37-mile length track with higher maximum authorized speed (MAS) and is shared between passenger and freight service. A further section of 62-mile of track is passenger only with an MAS of 96 mph. A side track of freight only, single line operation with MAS of 66 mph branches off where the high-speed passenger service begins. The risk results are indicated on a segment-by-segment basis. The model developed predicts an overall accident rate with an ABS system of 0.092/million train miles (0.092/MTM) for the entire corridor (0.052/MTM) with a PTC1 system. The high-speed section with only an ABS accident rate is 0.335/MTM, which represents about a factor four increase over the overall corridor rate.

Amtrak's system-wide accident experience rate is 0.15/MTM. The prediction of Kokkin, et al. (1999) of the accident rate with ABS on the example corridor they considered is 0.166/MTM. It is hard to compare these numbers because of different "system" parameters, descriptions of the corridors and train frequencies. For example, the high-speed section of the authors' corridor has block lengths of 3,280 feet whereas the block length in the single track, freight-only section is 656 feet. Also, in the case of Amtrak, the accident rate values include all sections of varying lengths, block lengths, train frequencies and mix of different types of trains in the corridors (i.e., high-speed, freight, and commuter trains, etc., nationwide). It can only be surmised that the predicted accident rates are comparable to Amtrak's experience value within a factor of three.

The maximum annualized economic equivalent risk for the high speed section of the corridor is calculated to be about $25,000 per year with ABS and $10,000 with PTC 3.

The results on reduction in the risk due to the application of different levels of PTC are indicated in Table 10.

Table 10. Risk Reduction Level (%) with Different PTC Systems

Type of Accident		PTC1	PTC2	PTC3
Collision	Head-on	32	51	74
	Rear-end	13	13	13
	with MOW	26	29	32
Derailment due to broken rail		51	51	51
All Accidents		47	51	55

Source: Larech, et al. (1998)

The results indicate that with the use of positive train control systems, the overall risk can be reduced by as much as a factor of 2. Accident rates are almost directly proportional to the failure rates of the train control systems. The dramatic reduction in head-on collision rate between PTC1, PTC2, and PTC3 is a consequence of the assumed values for the failure rates of the respective train control systems. The annual failure rates assumed, respectively, for ABS, PTC1, PTC2, and PTC3 systems are $8x10^{-13}$, $2.4x10^{-13}$, $1.6x10^{-13}$ and $0.8x10^{-13}$.

Discussion: As the authors have pointed out, this approach has elements of a complex fault-tree based model, and a simple analytical approach. The model uses some of the parametric representation of the casualty results obtained from a more sophisticated computer analysis of the fatality and injury resulting in collision accidents and derailments. The model can be exercised reasonably quick on a spreadsheet and the sensitivity of the final risk results to variations in assumptions or input parameters can be determined. The analytical formulations of the various accident scenarios and probability estimations are based on physics of the accident situation; thus, the relationships between important parameters (such as train speed, block length, PTC parameter, etc.) and the risk can be visualized.

A drawback of this model is that the risk estimate is provided in the form of expected values (or averages over all possible levels of accidents). Although it can be useful to obtain a quick understanding of the average risk values, it is also useful to determine the probabilities of accidents that may lead to large casualties. The model in its present form does not do this second step. Thus, it does not provide a “risk profile.” However, the model may be amenable to an extension to include such a calculation feature.

3.1.5 Study on the Safety of High-Speed Rail Systems Intrusion Barrier Design

Objectives: This study conducted by Moyer, et al. of Parsons, Brinckerhoff, Quade and Douglas, Inc., was intended to evaluate the effectiveness of various types of intrusion prevention barriers at the shared rights-of-way for a high-speed rail system and to estimate the cost of each type of barriers.

Approach and Results: This engineering study by Moyer, et al. (1994) considered 28 transportation scenarios on the same ROW including the high-speed rail system, slower passenger and freight rail service, and highway. The guideways considered are: elevated, at grade, and below grade. The impact loads on the barriers for different types of derailment accidents involving maglev, conventional freight train, high-speed passenger train and highway trucks were evaluated. Also studied were the construction and repair costs for a number of designs of intrusion barriers. No specific risk assessment was made on the potential (or probability of) failures of different designs of the intrusion barriers caused by derailment accidents. Because of this, no additional review of this study is made.

3.2 HIGH-SPEED RAIL SYSTEM RISK ANALYSIS RESEARCH SPONSORED BY OTHER INSTITUTIONS

3.2.1 JR East Projects at MIT

Objectives: The objective of the series of research efforts undertaken, since 1993, jointly by the Center for Transportation Research at MIT and the Japan East Railway Co. (JR East) was to perform risk assessment studies to the railroad industry and its specific application to providing guidance to JR East policymakers on optimal investment strategies for improving passenger transportation safety.

In order to fulfill the above objective, a number of different research efforts were undertaken studying various aspects of the railroad operations, rolling stock maintenance, effect of environmental conditions (including operating the trains under potential earthquake conditions), grade crossing safety, human error-caused failures, risk mitigation measures, risk monitoring approaches and technologies, etc. (Odoni & Sussman, 1997). Summaries of the various research activities and their results to date are published by MIT (MIT, 1997).

3.2.1.1 A Framework to Monitor the Safety Performance of Transportation Systems

Approach and Results: In this study, Nasser and Odoni (1995) have developed an approach to measure the risk in a rail operation. The unit of measurement of the consequence of an accident is a weighted economic equivalent value of life, human injury, service delay, and property damage defined by a Safety Cost Index (SCI) as follows:

$$\mathbf{SCI(t) = \sum p_i\, x_i(t)} \tag{5}$$

where, SCI is the index for a certain measurement period 't', p_i is the price of safety outcome 'i' (i can represent the fatality, injury to passenger, injury to worker, property damage, etc.) and 'x_i' is the number of casualties of type i occurring during the period t. The various cost equivalents of fatalities and injuries are estimated for different countries by the economic theories of 'society's willingness to pay' and 'human capital.' The fatality cost in Japan is estimated at $0.26 million which is 10 percent of the fatality cost in the US at $2.6 million (close to the $2.7 million value used in other studies sponsored by U.S. DOT). Other cost values for Japanese conditions used by the authors for calculating the SCI for the JR East system are indicated in Table 11.

Table 11. Casualty Costs Used in JR East Risk Assessment

Casualty Type	Value per person
Fatality to Passengers, RR Workers, Third Party Persons	256,000 ($)
Injury to Passenger, RR Worker, Third Party Persons	9,700 ($)
Delay in Passenger service	20 ($/hr)
Refund for Canceled Service	10 ($)

Source: Nasser & Odoni (1995)

The authors have calculated the SCI for each quarter and the total using the above equation that contains historical accident data for each calendar quarter for the period June 1987 to March 1992 for all of JR East system lines, and an assumption of 500 passengers per train. The fatality costs amount to about 30 percent of SCI whereas the refund cost due to canceled trains amounts to 50 percent of SCI. Within the fatality cost, 80 percent of the cost is attributable to third party fatalities. This indicates that the system is very safe for the passengers and the railroad workers and most accidents involving fatalities occur due to collisions at the grade crossings.

As discussed in Section 2, all societies seem to attribute a higher value for an involuntary fatality compared to the fatality from accidents in which the person is perceived to have undertaken a voluntary risk (such as a subcontract worker or a person crossing the tracks at a grade crossing). The risk perception on the part of the society has been taken into account by Nasser and Odoni by multiplying the 'actuarial cost' of a detrimental outcome on human beings by a risk conversion factor (RCF) which enhances the cost depending upon whether the accident was caused by natural forces or manmade, and whether the accident resulted in minor or catastrophic casualties. Table 12 shows the values used by the authors for the RCF.

The perceived safety cost index (PSCI) is also obtained for each quarter for each of the casualty types and compared with the safety cost index. It is seen that both indices track very closely in their variation with time indicating that they are closely correlated. It is seen, however, that 53 percent of all perceived risk (as evaluated by the PSCI) is due to fatalities. Injuries contribute 25 percent of PSCI. Also, within each category of casualty, on-board passenger fatality and injury dominate the PSCI, respectively at 39 percent and 92.4 percent. As indicated in Section 2, people will tend to equate high-speed rail service with airline service and, therefore, the perception of risk will be quite different from those of low-speed transportation systems; hence, perceived risk values need to be determined. The work of Nasser and Odoni clearly indicates that the perceived injury risk is an important factor in the overall risk. Therefore, in any rail accident risk analysis, the on-passenger injury cannot be ignored and should be given a weight at least equal to that of fatalities.

Table 12. Risk Conversion Factors Used in JR East Risk Assessment

Affected Person or Event	RCF
Passenger on the train	100
Other passenger (say, in an automobile at grade crossing)	5
Third-party person	1
Sub-contract Worker	5
Employee on duty	100
Employee off duty	100
Delay	1
Physical Damage	1

Source: Nasser & Odoni (1995)

The authors have evaluated the impact of exogenous factors such as rainfall, traffic pattern and increase in passengers using the railway and the passenger-mile by obtaining statistical correlation parameters and t-statistic coefficients for the effect on SCI of each of the exogenous variables as well as time. It is concluded that rainfall has significant effect on causation of accidents and hence on SCI. Similarly, traffic density has considerable effect on the risk as indicated by SCI. The authors conclude that using only the fatality as a risk measure presents a very distorted picture of the risk. It is shown that the operational delays contribute heavily to the "risk" as measured in economic terms and that the perceived risk values are dominated by the cost of injury to the passengers.

Discussion: This study does not evaluate the probabilities of accidents occurring or the potential fatalities or injuries from such accidents. The analysis is based entirely on historical data on actual fatalities, injuries, train delays, etc.; parameters experienced in JR East system over the period June 1987 to March 1992. There is no predictive capability in the model other than to evaluate the relative importance of different measures of casualties and other costs. To the extent that the study concludes that on-board passenger injuries is a measure that is as important as the fatality measure, the study has contributed significantly to the understanding of the overall risk.

3.2.1.2 Risk Assessment in East Japan Railway

Approach and Results: Horiuchi and Fukuyama (1997) have conducted a global risk assessment of the operations of JR East. The study was initiated to identify the types of risks existing in the current operations at JR East and the magnitudes of these risks. The primary aim of the study was to develop a tool for better decision making in safety management.

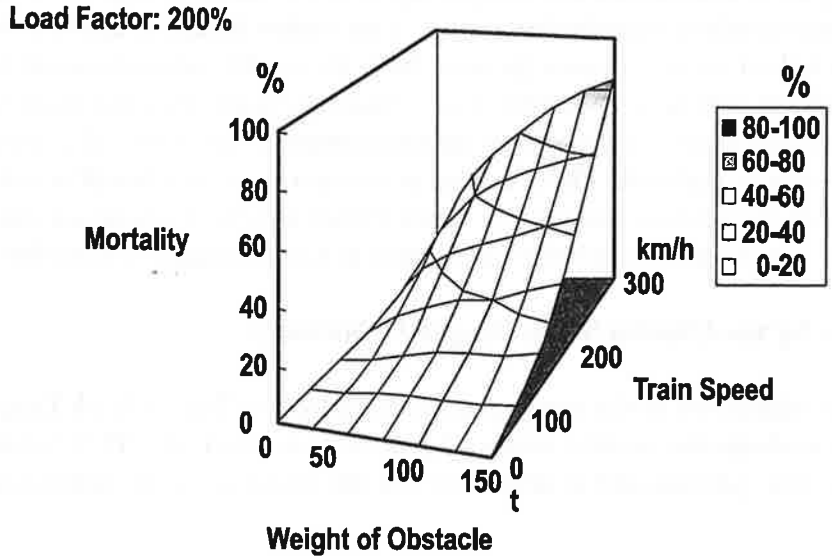
The researchers have used the extensive accident and incident data base of JR East. This database, as of March 1996, contained 2217 accident data and 92,800 incidents. First, the accidents are categorized by different causes (nature-caused, signal overrun, signal malfunction, rolling equipment failure, grade crossing collisions, etc.). Subsequently, the probability of such accidents occurring are calculated from the extensive operation mileage data. The possibility of rail incidents (which originally did not cause any accidents) transitioning to accidents causing potential passenger fatality are considered through a system of 'subjective weights' for each incident. For example, if an experienced incident is judged to have a high potential to have become an accident, it is given a weight of 1. If the transition possibility is moderate, the weight assigned is 0.1, and 0.01 for an incident having a "low" possibility of becoming an accident and 0.001 for very low possibility of incident-to-accident transition. The potential number of accidents for each segment of a line is then the sum of weighted incidents for each category of transition together with the number of actual accidents multiplied by an effectiveness factor. The effectiveness factor is determined from those segments in which there were accidents and incidents. The value of the effectiveness factor is such that on these segments, the product of the effectiveness factor and the potential number of accidents is equal to the actually experienced number of accidents. The average effectiveness factor is then used for the entire line of interest.

The only consequence of interest considered in the study was the passenger fatality. The expected value of fatalities in each accident is calculated using a fatality function (one for collision accidents and another for derailments) which uses the train speed, car load factor, and weight of the obstacle in collisions as input parameters. An example of how the fatality function changes with train speed and weight of obstacle, when the load factor in the train is 200 percent is indicated in Figure 4.

Detailed risk calculation results are presented by the authors for 10 different lines in the JR system. The risk results are presented in the form of bar graphs of the annual expected number of fatalities per km of the line for each of the 10 lines. The graph indicates the contribution to the risk by various accident-causing parameters such as train separation, train fire, errors in signaling, incorrect track maintenance work, car failure, signal system failure, natural hazard, collision with automobile, signal overrun, etc. Also presented is a risk profile of the expected number of fatalities per accident as a function of the probability of such an accident (in number per year) occurring. This result is shown in Figure 5. This type of presentation clearly illustrates the influence of the various types of accident causes and their consequences.

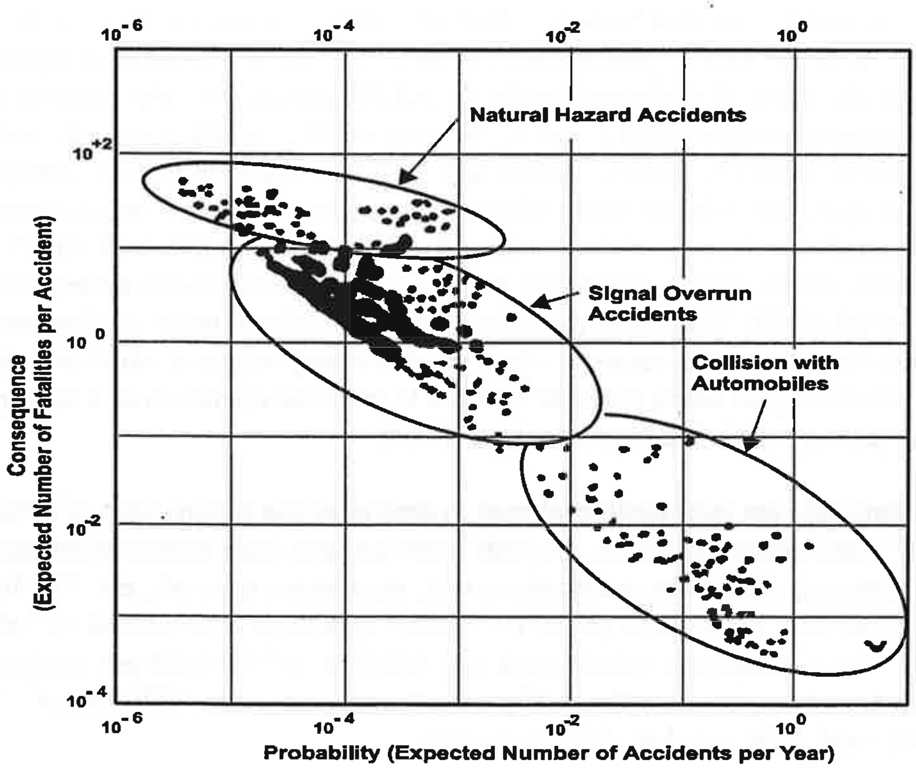
The results further indicate that the existing risk on the JR East system is about 1.1 fatalities per year. The largest contributor to this risk is natural hazards (about 45 percent) followed by signal overrun (25 percent), followed by train collision with automobiles principally at grade crossings (14 percent).

Discussion: The analysis presented in this study is useful in predicting the existing risk from the available accident data. The single most important assumption made is that the risk is constant over the period of time which is spanned by the database, because it is tacitly assumed that the accident rate as expressed in number of accidents per year is constant (and is obtained by dividing the total number of accidents since 1986 by total number of years of data). It is uncertain whether this assumption is valid in view of the fact that traffic has increased substantially since 1986 when the accident data collection was initiated. In addition, the model used does not have any predictive capabilities. No attempt has been made in this study to cast the results in such a manner as to make them useful for predicting future risks. That is, the analysis results have not been presented in the form of normalized units (number of accidents/train km) and their dependence on type of traffic, traffic density, operational attributes, track characteristics, etc.



Source: Horiuchi and Fukuyama (1997)

Figure 4. Example of a Fatality Function



Source: Horiuchi and Fukuyama (1997)

Figure 5. Risk Profile for the JR East System

Notwithstanding these limitations, the analysis approach is sound in that the results are presented in terms of various accident-contributing causes. This makes it easy to discern the degree of influence on the risk of various causes (as seen from the results, natural disasters cause 45 percent of the risk). It will be very helpful if the results from all other risk studies are presented in the format used in this study, i.e., graphical representation of the degree of contribution of various causes to the overall risk. The database contains a large number of accidents and incidents. This rich data can be analyzed in future efforts to obtain important information on the magnitude of the various risk parameters applicable to a high speed rail corridor.

3.2.2 Analyses by the Charles Stark Draper Laboratory

Objectives: The objectives of the analyses conducted by the Charles Stark Draper Laboratory (CSDL) were to evaluate the relative safety of positive train control (PTC) systems compared to existing train control systems, and to determine the rail accident rate reductions by the provision of PTC.

The reduction in accident rates by the provision of different PTC systems has been studied by two groups.

3.2.2.1 Safety Analysis of ARES

Approach and Results: Weinstein, et al. (1987) investigated the reduction in accident rates if the Advanced Railroad Electronics System (ARES) developed by Rockwell, were to be implemented by the Burlington Northern Railroad (BN). CSDL developed an analytical model that could predict the safety of operations under the ARES and compare the existing safety levels in the railroad operating without such a system. The input to the model developed includes the statistical information on the reliability (failure rates and error rates) of various subsystems and components. The approach is based on the Markov Transition model. The model computes the potential accident rate for the reportable accidents for the railroad system with ARES. This value is then compared to the existing accident rate with its existing train control systems to determine the relative safety of ARES. The model provides information about which components of the system contribute the most to the accident rate. The model also indicates when certain operational decisions impact safety (such as whether to continue operation in a backup mode, or to wait until the primary mode hardware has been fixed).

A number of submodels are indicated/developed to determine the failure rates of subsystems such as the VHF radio communications, wayside interface unit, train communications, GPS, on-board data management unit, token enforcement unit, microwave network, etc. The human failure rates for operators involved in any of the control systems is estimated at 10^{-5} errors per person per hour. Other component failure rates vary between 10^{-6} per hour per component (microwave signal receiver combiner) to 10^{-4} per hour per component (VHF radio). The model has used the 1985 and 1986 accident data for the BN.

Discussion: The results indicate that a reduction by two orders of magnitude in the annual rates of accident is possible for those accidents that can be directly attributed to "control system failures and associated human failures." The 1984-85 average accident rate for BN attributable to control system failures is about 50 per year. (In this analysis, "control system" is defined as signal system hardware plus locomotive engineers and railroad dispatchers.) The predicted rate with the full deployment of ARES is 0.5 accidents/year. Virtually all accidents caused by failures of then-current train control systems on BN were attributed to the failure of the human element (responsible for closing the sensor-to-actuator control loop). The authors indicate that while the human element is also a part of the ARES control system, the architecture of ARES is such that the human does not represent a single-point failure mode. That is, there are no human failure events that can transition to an accident because ARES clearance enforcement hardware operate in parallel with the train operator. The human can contribute to an accident only as a part of a multi-event sequence of independent hardware failures and human error events. The model does not explicitly calculate the magnitude of the accidents that are possible from the failures of the ARES components; the presumption is that they would be the same as with current "control system" accidents.

3.2.2.2 Safety Analysis of the Positive Train Separation System

Approach and Results: Schor and Rosch (1994) have used a model similar to that developed by Weinstein et al. (1987) to evaluate the effectiveness of the positive train separation (PTS) system developed by Harris Corporation (later GE-Harris) in reducing accident frequencies, especially train-to-train collisions. The objective of the model was to assess the safety implications of implementing the proposed on-board safety functions of PTS by BN and Union Pacific (UP). The approach in this analysis is similar to the previous study in that a Markov-type model is used to address those situations where some trains operate without automatic authority and speed limit enforcement and therefore become vulnerable to operator error. Human error transitions are spliced in this model onto the availability models (for different types of hardware elements in the system) and the results of all models are combined to predict the accident rate. The authors point out that no absolute numbers on the accident rates were generated by the models and that the model developed can be used to compare the performance of the railroad system with and without the provision of a PTS system. The results indicate that about two orders of magnitude of reduction in the accident rate attributable to the on-board train control system can be achieved.

3.2.3 Study by the Volpe Center for the Railroad Safety Advisory Committee

Objectives: The objective of the study reported by the Railroad Safety Advisory Committee (RSAC) in this report to the FRA Administrator and undertaken by the Volpe Center was to develop a risk assessment model taking into account the historical accident information from U.S. railroad experience and to determine the extent to which the risks can be reduced by the introduction of advanced train control (ATC) systems and assess the costs of such an undertaking.

Approach and Results: The Railroad Safety Advisory Committee (RSAC, 1999) issued a report to the FRA Administrator on the implementation of PTC systems on U.S. railroads focusing on the safety dimension of PTC. The report describes in detail and compares the features of current projects in North America on the implementation of ATC systems of which the PTC is considered a part. The primary function of PTC, from the RSAC working group perspective, is to prevent train-to-train collisions, enforce speed restrictions (including civil engineering restrictions on curves and bridges and due to temporary slow orders), and provide protection to roadway workers and their equipment.

In order to achieve the above objectives, RSAC indicated the implementation of a PTC with four levels of sophistication of technology (and associated costs), namely Level 1 to Level 4, with each higher level consisting of the previous level technology or functions as a subset. Level 1 addresses the "core functions" of the PTC, Level 2, in addition, contains features to issue specific movement authorities and the reporting of train and roadway crew locations to the authority issuer. In Level 3, PTC wayside interface units (WIUs) monitor each mainline wayside switch and signal. In Level 4, additional protective devices such as slide fences, anemometers, highwater, dragging equipment and hotbox detectors are provided. Also, additional track circuits, track continuity circuits and other risk reduction systems for broken rail detection are included.

Data from 6400 reportable accidents that occurred during 1988 thru 1995 were reviewed by an expert panel subgroup of this RSAC working group and segregated into accidents that could have been prevented by different level PTCs had they been in place. Further accidents were segregated into several categories of preventability. These categories of preventability of an accident by a PTC are as follows:

1) Y - Completely preventable by PTC
2) N - Not preventable by PTC
3) M - May be preventable by PTC under certain circumstances
4) R - PTC will mitigate the cost of the accident
5) S - PTC may mitigate the cost of the accident
6) O - Optional protection from collisions with trains when the track equipment is outside the limits of the track equipment's authority.
7) W - Track machine collision with another track machine - not preventable with current technology

The RSAC report also has discussed a corridor risk analysis model (CRAM) developed to evaluate the risk reduction potential of PTC. The model is first calibrated with actual rail accident data from which certain regression parameters are obtained. These parameters are then used to "predict" the number of preventable accidents that can occur (in the absence of PTC) on each link of a rail traffic corridor. The consequence of each accident is represented in societal cost dollars, i.e., as the sum of society's willingness to pay to avoid casualties at the rate of $2.7 million for each fatality, $100,000 for each employee injury, $55,000 per passenger injury, and $500 per person evacuated plus any direct property damage cost.

CRAM is based on the statistical analysis of rail accidents that occurred during the period 1988-1995 obtained from the FRA Accident and Incident Data Base together with other data inputs from Association of American Railroads (AAR) and other participating railroads and railroad employee organizations. A subset of the full set of accidents were reviewed as to its location, categorization in terms of the preventability by one of the four PTC levels defined earlier, track and local geographics characteristics at the location of the accident, traffic flow (both passenger trains and freight trains), length of the link (between principal switches on the main line), and the number of fatalities or injuries, if any. Then the PTC preventable accidents, weighted by exposure (ratio of number of accidents on each link to the length of the link where the accident occurred) are used as the dependent variable. The number of accidents on each link is assumed to follow the Poisson statistics. The dependent variable is assumed to correlate with a number of track characteristic variables, train speed, and the traffic density by the following regression equation:

$$\mathbf{E(N)/\ Exposure = exp\ [A_0 + A_1\ log(cars) + A_3\ log^2(cars) + ...+ A_k\ X_k]} \qquad (6)$$

where, E(N) is the expected number of accidents which are preventable by PTC, exposure is the measure of the exposure, namely, the length of segment between switches, "cars" represents the number of trains on the link (indicating the traffic density), X_k representing other independent parameters such as the number of parallel tracks, number of switches on the link, highest maximum speed, percent of length of link under control method of operation, type of curve on the track, etc., and the coefficients A_k are the regression coefficients. The regression coefficients are obtained from a set of 678 accidents for which complete data were available. These regression coefficients are then used to predict the expected number of "preventable" accidents on each mainline link (in the presence of PTC) given the characteristics of the track, speed and traffic density on the link.

The actual fatality and injury data from past accidents are used to develop a consequence measure expressed as the average rate (averaged over all preventable accidents) of fatality per accident, passenger and employee injuries per accident, and track and equipment damage costs per accident. High and low values for each category of casualty are also determined. The results are provided for each of passenger train accidents and freight train accidents. Table 13 shows these results from the averaging of the consequence data from a set of 819 PTC preventable accidents. In the risk analysis model prescribed by RSAC in each accident, all types of casualties are assumed to occur at their average rate. The total preventable cost of each accident is then obtained by the societal cost to prevent the type of casualty times the average number of casualty of that type.

This model was applied to 183 rail corridor sets in the U.S. consisting of 8001 links for which geographic, track, traffic density, and track attributes data were available. The results indicate that, except for about 20 corridors, the average cost per mile of preventable accidents were about \$1/mile (and in many cases lower). The risk results in terms of cost saved by the provision of PTC on each link can be compared to the cost of installing and operating the PTC. RSAC determined that the deployment cost to equip all Class 1 railroads with PTC Level 1 would be about \$1.2 billion and \$ 7.8 billion for PTC Level 4. The benefits from avoided accidents are estimated to be, respectively, \$500 million and \$850 million.

Table 13. PTC Preventable Accident Consequence Magnitudes
(Average overall accidents)

Cost Category		Avg. Fatalities per Accident	Injuries		Damages	
			Passenger	Employee	Track	Equipment
Passenger Trains	High	0.9843	3.3621	2.0517	$32,107	$493,515
	Low	0.1509	1.9245	1.9434	$19,885	$323,356
Freight Trains	High	0.0938	0.2285	0.7031	$26,949	$265,906
	Low	0.0657	0.1564	0.5125	$26,313	$222,633

Source: RSAC (1999)

Discussion: This model is based on the actual railroad accident data and is dependent on expert opinion as to which one of the accidents could be preventable with PTC. The regression coefficients can be used to estimate the number of preventable accidents given the characteristics of the corridor; but the prediction of only preventable accidents is not sufficient to determine the overall risk in a system. This model currently has no predictive capability on the occurrence of nonpreventable accidents, since such accidents were not part of the regression analysis. This model would need to be adapted to predict other risks in a new high-speed rail system corridor with multi-use right-of-way (ROW). The model contains very useful information that can be integrated into other 'predictive' risk analysis models.

3.3 HAZARDOUS MATERIAL RAIL TRANSPORTATION RISK ANALYSIS

3.3.1 FRA Sponsored Research

Objectives: In response to NTSB recommendations related to the transportation of hazardous materials in tank cars, the FRA sponsored, in the early 1990s, several risk analysis studies to evaluate the relative risks posed by different hazardous material - tank car combinations. The objective of these studies was to use the risk analysis approach to developing performance-based regulations.

Approach and Results: A probabilistic risk methodology was developed to assess the relative reduction in the overall risk to the population when structural safety devices are provided on tank cars (Raj and Turner, 1992). The probability of mainline train accidents, and the conditional probabilities of a tank car in a consist being damaged and suffering a puncture were determined from FRA-published accident statistics for the years 1985 -1990. Based on the tank car puncture data collected by the Railway Progress Institute (RPI) and the AAR, the conditional probabilities of different puncture sizes occurring under different conditions are obtained. Also, from the research work of AAR, the reduction in puncture probability due to the provision of head shields, shelf couplers, jacketed insulation, increased shell and head metal thickness is obtained. Combining these accident and conditional probabilities, the overall probability of sustaining a puncture of a given size is determined.

The consequences of the hazardous material release are dependent on the physical and chemical properties of the material released from the tank car, the environmental conditions (including the weather) at the location of release, and the type of behavior of the chemical (fire, toxic vapor dispersions, explosions, etc.) and the local population density. Different chemical behavior models (based on physical and thermodynamic models) were used to calculate the "hazard area" from the release of the chemical from different puncture sizes, under different weather conditions, and types of chemical behavior. The consequence measure used is the number of people potentially exposed to the deleterious effects of the chemical and is obtained by multiplying the area of hazard and the local density of population.

The model results are presented in the MIL-STD 882D parameters. The correspondence between MIL-STD 882D frequency categories and actual occurrence frequencies used in this model are indicated in Table 14. Similarly, the correspondence between hazard parameters and people exposure values used are shown in Table 15. The national railroad system is the "system" for correspondence to the MIL-STD definition.

Table 14. Relationship Between MIL Standard 882D Probability Categories and Numerical Frequency Values

Mil Standard Probability Categories	Number of Events Assumed to Occur per Year	Mean Frequency of Events/year	Events Occur Approximately Once	Ratio of Event Frequency to that of "Frequent"	
				Range	Log Mean
Frequent	>500	500	a day	>1	1
Probable	10 - 500	70	a week	$2x10^{-2}$ to 1	$1.4x10^{-1}$
Occasional	1 - 10	3	a season	$2x10^{-3}$ to $2x10^{-2}$	$6.3x10^{-3}$
Remote	0.1 - 1	0.3	in 3 years	$2x10^{-4}$ to $2x10^{-3}$	$6.3x10^{-4}$
Improbable	0.01 - 0.1	0.03	in 30 years	$2x10^{-5}$ to $2x10^{-4}$	$6.3x10^{-5}$

Source: Raj and Turner (1992)

Table 15. Relationship Between MIL Standard 882D Severity Categories and Numerical Exposure Values

Mil Standard Categories	Number of Persons Exposed		Ratio of Exposures to	
	Range	Log Mean	Range	Log Mean
Catastrophic	>1000	1000	>1	1
Critical	30 - 1000	170	0.33 to 1	$170x10^{-3}$
Marginal	1 - 30	6	10^{-3} to $3.3x10^{-1}$	$5.5x10^{-3}$
Negligible	≤1	<1	$<10^{-3}$	$<10^{-3}$

Source: Raj and Turner (1992)

This risk model was applied to evaluate a national risk arising from the transportation of a number of 'poison by inhalation' (PIH) and 'flammable' materials over the entire U.S. railroad system and to assess the differences in risk between different chemicals. Also performed was the comparison of risks when the same chemical was transported in different DOT specification tank cars. The risk is expressed in terms of the exceedance annual probability of exposing more than a specified number of people as a function of the number of people exposed and these results were superimposed on the MIL-STD risk matrix. The results indicate that, in general, there is an order of magnitude reduction in the overall risk when a poison by inhalation material is transported in DOT 105 cars compared to that when transported in DOT 111A tank cars. FRA has used this methodology to justify the issuance of certain hazmat regulations (HM 175A and HM 201) pertaining to transportation of PIH chemicals in different types of rail cars (Raj and Pritchard, 2000). The risk analysis methodology indicated in this study was extended to cover other hazardous materials, especially self-polymerizing materials and self-heating materials. The potential damage to people and property from metal debris from exploding tank cars is also considered in the consequence modeling.

3.3.2 Inter-Industry Working Group Research

Objectives: The objectives of this study were to evaluate the state-of-the-art in hazardous material rail transportation risk assessment modeling and to develop a standard model that the entire industry could use.

Approach and Results: A risk analysis effort was funded by the Inter-Industry Working Group comprising the AAR and the Chemical Manufacturer's Association (CMA). This effort was to develop a very detailed model that would take into consideration the accident statistics over different classes of track, include accidents in railyards and consider different speeds of operation and other track and operational parameters specific to each segment of the transportation corridor. The consequence of hazmat releases are calculated using physical models to estimate the hazard areas. The results are expressed in the traditional F-N curve. More details of the actual values used for the accident rates and other criteria are not available at this time since the model is considered to be an industry proprietary model.

3.4 OTHER RELEVANT RESEARCH PERTAINING TO RAILROAD RISK ASSESSMENT

3.4.1 FRA Sponsored Fire Safety Research

Objectives: The FRA has sponsored research in other areas of concern for passenger rail transportation systems. One area is the reduction of casualties due to fires in passenger rail equipment as a result of collisions/derailments or other causes.

Approach and Results: The FRA published guidelines in 1989 that specified flammability and smoke emission tests and performance criteria for intercity and commuter rail vehicle materials. Although the FRA tests and performance criteria provide a screening tool to minimize the use of particularly hazardous materials, the reduced risk of using more fire retardant materials has been difficult to quantify. Peacock et al. (1993) identified an alternative approach based on quantitative heat release rate (HRR) data and the conduct of hazard analyses using computer models to more accurately evaluate the fire performance of passenger rail materials. In 1999, the FRA issued passenger rail equipment safety standards which made mandatory the tests and performance criteria contained in the 1989 guidelines. Based on the results of ongoing research conducted by the National Institute of Standards and Technology (NIST), the FRA has also permitted the use of the Cone Calorimeter as a test method and HRR performance criteria data to evaluate seat components and small parts as an alternative to the previously used tests.

Discussion: The objective of the FRA-sponsored NIST research study is to provide a quantitative analysis tool which will consider tenability time and minimum necessary safe evacuation time to evaluate risk. Tenability time is the time to passenger incapacitation. The minimum necessary safe evacuation time is defined as the time that passengers require to evacuate from the end of the rail car. Quantitative hazard analyses have been conducted which calculate the tenability (based on HRR) and minimum required evacuation times for a single level passenger coach car, and bi-level dining and sleeping cars. The NIST hazard analyses have determined that, depending on the size of the ignition source and subsequent fire, other car design elements, such as fire detection and fire suppression, may have a larger impact on increasing tenability and available evacuation times and thus could reduce passenger risk more than changes to materials.

3.4.2 American Public Transportation Association (APTA) Recommended Practice

Objective: The FRA requires that railroads conduct fire safety analyses and determine what the acceptable risk is for passenger rail materials which may not meet the required performance criteria. However, the FRA regulation does not contain specific guidance on how to determine acceptable risk. Accordingly, it was necessary that this guidance be developed for passenger railroads.

Approach and Results: An APTA Passenger Rail Equipment Safety Standards (PRESS) Task Force was established in 1996 to develop standards and recommended practices to assist the railroads in implementing the FRA passenger rail equipment rule requirements issued in 1999. The Task Force consists of passenger railroad staff, consultants, and FRA and Volpe Center staff. As part of the Task Force efforts, the PRESS Systems committee developed a recommended practice which describes the steps necessary to analyze the risk posed by different types of passenger rail equipment, ignition sources, the quantity and type of material, and kind of operating environment. An important first step was to gather and review fire statistics, both by individual passenger railroad and for similar types of passenger railroad cars. The severity and probability categories used in MIL-STD 882D were adapted to provide a risk assessment matrix to evaluate fire scenarios.

Discussion: All of the completed fire safety analyses conducted by the various railroads have not yet been reviewed by the FRA. However, preliminary review of some of the railroad analyses does indicate that the MIL-STD 882D risk assessment approach can be adapted successfully for evaluating rail passenger equipment fire risks. A key requirement is to develop statistical data bases which can be used to identify fire incidents and related maintenance issues to ensure that a systems approach to fire performance is implemented.

4. FINDINGS AND RECOMMENDATIONS

In this study, several risk assessment projects and models related to the transportation of passengers on railroads have been reviewed. Specific attention was focused on the application of the models to determining the risks in a high-speed rail system. Also reviewed were some of the basic concepts of risks and society's perception and acceptability of risks in regard to transportation and other technological systems. Indicated below are some of the findings from this review effort.

4.1 FINDINGS

4.1.1 Rail Transportation Risk Models have a Wide Range of Complexities and Details

The basic approach to determining the risk in a transportation system such as the high-speed rail system is well understood and used in all of the studies reviewed. Risk analyses attempt to estimate the probability of occurrence (generally, on an annual basis) of events or accidents and the consequences of such events expressed in some understandable measure such as fatalities, injuries, property damage, overall economic penalty, etc. The differences in the approaches lie in the level of detail of evaluation of potentially detrimental scenarios and the level of aggregation of the failure events. Also, different models express the final results in different ways; some express the results in qualitative measures (MIL-STD 882C), others in single values of probability and consequence (expected value presentations), and others in the form of detailed risk profiles for different rail segments and for a single transportation corridor. The usefulness of the results for a designer or a regulatory agency depends on the objective of the analysis; that is, whether a screening analysis is being performed or a design study is being attempted.

4.1.2 Society's Perception of Risks is not Universally Considered in the Models

The importance of considering the perception of risks by the general population in regard to any new technology has been demonstrated in a number of studies. In fact, the research of Slovic and Lichtenstein (1979) has demonstrated that the general population seems to consider railroad travel disaster potential as high as in air travel. This comparison with air transport will only increase with the introduction of high-speed rail systems which will be competing with the short haul air service. In spite of such awareness, many of the risk models applied to high-speed rail systems do not explicitly take into account the public perception issue in the analyses. The exception to this are the approaches of Nasser and Odoni (1995) who use significant risk enhancement factors to take into account society's perception of the fatalities and injuries in rail accidents. Vrijling, et al. also consider this since such consideration is a part of the European regulatory guidelines.

4.1.3 Significant Differences Seem to Exist between the European and U.S. Risk Assessment Requirements

First, in the European methodologies both the societal risk and individual risks are evaluated, while in the U.S. it is always the societal risk that is calculated. Second, the European and Japanese calculations always indicate the risk profile with specific identification and degree of influence of the controlling parameters on the overall risk. Third, the European requirement for societal risk variation with the magnitude of casualties seems to be more severe than has been proposed in the U.S. (at least in one study, Bing, 1992). In Europe, the risk, as expressed in the annual probability of exceedance, must vary (drop off) as N^{-2}, whereas in one of the studies the proposal for the U.S. high-speed rail system is for a $N^{-(4/3)}$ variation, where N is the number of casualties. Both systems agree at the N=1 level for the annual probability of exceedance. It seems likely that the European standards demand a higher level of safety at higher casualty levels.

4.1.4 The Confidence Level of the Risk Assessment Results are Rarely Presented

It is well known that the results of risk assessment models are as accurate as the input values for various parameters. In many cases, the values for some of the key parameters (especially, human errors) are rarely known with any degree of precision. Hence, the risk results can vary by several factors or even by an order of magnitude. Many regulatory "accept or reject" decisions may be made by reviewing the results without the benefit of the uncertainty in the results arising from "natural variations" in the values of the parameters. Analysis of the sensitivity of the final risk result to the range of variation of the parameter values has, however, been considered by Larech, et al. (1998) and the RSAC (1999). Presentation of sensitivity results as well as the natural error 'bands' in risk calculations must be made an integral part of any assessment studies.

4.1.5 Risk Associated with Software Failures are not Explicitly Presented

The high-speed rail system and other railroad systems currently depend very heavily on system software for operational performance. However, none of the studies reviewed indicate any consideration of this important aspect. The work at CSDL takes this into account, indirectly, in the evaluation of PTC failure risks. The U.S. regulations, recently promulgated by the Federal Railroad Administration (Title 49, Code of Federal Regulations, Part 238.103, "General System Safety Requirements") explicitly require the consideration of software safety but there exists no specific guidance on how this can be considered and what level and degree of software errors need to be evaluated.

4.1.6 The Usefulness of Application of Screening Type Risk Models to a Complex and New High-Speed Rail System is Uncertain

The regulations in 49 CFR Part 238.103 require the development of a system safety plan using the MIL-STD 882C as a guide. Unfortunately, the regulations do not define the various MIL-STD 882C risk matrix parameters in any quantitative terms applicable to a railroad operation. For example, it is not very clear as to the level at which the fatalities in a railroad accident will become "catastrophic." Similarly, no guidance exists to define the occurrence frequency domains. As shown by Hadden, et al. (1992), and Raj and Prichard (2000), the use of MIL-STD approach cannot be performed without resorting to actually defining numerical equivalencies. Such equivalence assignments are very subjective and may result in several orders of magnitude error in assigning risks. For a highly visible technology such as a high-speed rail system which the public may perceive as a "plane on the ground," errors of such magnitude are not acceptable. Therefore, one should question the usefulness of an MIL-STD approach to high-speed rail systems unless there is an expert consensus opinion on the definitions of the subjective risk categories.

It is worthwhile to note that 49 CFR Part 238.103 requirements on system safety assessment apply only to "operating railroad passenger equipment" and not to other equipment, operational parameters or employee training aspects of railroad operations.

4.1.7 Intermediate Complexity, Parametric Models May be Adequate for Assessing High-Speed Rail System Risks

The risk modeling approach proposed by Larech, et al. (1998) and that described by RSAC (1999) has the required features for evaluating the risks from a high-speed rail system. These models take into account the current accident data and provide either statistically evaluated parameters or parameters and results obtained from a combination of physical modeling and statistical analysis. However, additional improvements need to be made to each of the models before they can be universally used. The Larech, et al. model at present evaluates only the risks arising from failures in PTC. The model should be expanded to include other types of accident initiating events (particularly human failures) and casualties (fires) and present the results in the form of risk profiles. The advantage of this model is that it is semi-empirical in that many of the complex calculations of fatalities and injuries are reduced to parametric equations. The RSAC model at present determines only the opportunity cost of not having a PTC in a line segment. However, with some modifications, the model should be able to predict the total number of accidents in a given line with specified features, traffic and train speed.

4.1.8 No Detailed Comparison of Pre-Regulation and Post-Regulation Risks has been Performed

None of the models reviewed has evaluated the risk reduction from the promulgation of the new set of regulations in the U.S. (Passenger Equipment Safety Standards, 49 CFR Part 216, et al., May 12, 1999). It will be interesting to determine the extent of passenger risk reduction from the pre-regulation risk in operating railroads and its potential impact on high-speed rail system risks. Again as indicated earlier, the rules apply only to rolling equipment. None of the models reviewed identified the breakdown of the risks caused by rolling equipment malfunction, track-caused failures, signal and other control system failures, and human failures. The effectiveness of the new regulations in preventing high-risk failures should be determined.

4.1.9 There is Wide Disparity between the Results of Different Investigators on the Level of Reduction in Rail Accident Risks by the Use of Positive Train Control Systems

Three institutions have evaluated the risk reduction by the provision of PTC systems. The calculated values for the reduction in rail accident risk (i.e., the number of accidents preventable with the PTC) vary considerably between the different researchers. Table 16 summarizes the results from three investigators. The discrepancy in the predicted risk reduction values may be due to the differences in the definition of PTC preventable accidents used by the different researchers. Therefore, there is a need to develop precise and consistent definitions for the terms used in assessments related to the risk reduction benefits from the use of PTC.

Table 16. Summary of Calculated Accident Rate Reductions with PTC

Institution/Researcher	RSAC PTC Levels			
	1	2	3	4
MIT[1] – Larech, et al. (1998)	47	51	57	NA
CSDL[2] – Weinstein, et al. (1987)	NA	NA	≈99	NA
CSDL[3] – Schor and Rosch (1994)	NA	NA	≈99	NA
RSAC[4] (1999)	7.4	9.2	10.3	14.9

NOTES: (1) The reductions with PTC are with respect to accidents that occur on systems which have ABS.

(2) The reduction due to the provision of ARES in accident rates directly attributable to control system and human failures.

(3) Same as (2) except PTS, not ARES.

(4) RSAC numbers refer to the reduction of those accidents that are deemed preventable with PTC and do not refer to all reportable accidents.

The review study performed in this effort did not include a detailed review of either prior U.S. regulations or the current regulations and how they may affect the risks.

4.2 RECOMMENDATIONS

These recommendations are not presented in any specific order of priority.

1. FRA should provide guidance on the meaning and approximate numerical equivalence of MIL-STD risk parameters as they apply to railroad operations, in general, and high-speed rail systems, in particular. This may be a task for an expert panel.

2. The results of complex structural dynamics models that calculate passenger injury and fatality should be expressed in parametric equations with important independent variables such as the train speed, structural characteristics of the passenger car, mass of the object impacted with, occupancy density in the car, etc.

3. Additional study should be conducted to expand the features of the intermediate complexity models (such as the ones due to Larech, et al. and RSAC). The models developed should be amenable to execution on PC-type computers in reasonable CPU

time periods. The results should be presented in a graphical or tabular manner to highlight the contribution from or the effects of various important sub-systems on the overall risk.

4. The risk results should include all measures of casualties including fatalities and injuries to passengers, railroad workers, and third-party persons and property damage. Also, societal perception of risk for the particular technology should be factored in.

5. A study should be undertaken to evaluate the risk reduction achieved by the current passenger equipment safety standards and other FRA regulations related to railroad operations.

6. Consistent definitions for risks and risk reduction in rail accidents should be used for comparable effectiveness when train control systems are to be judged.

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