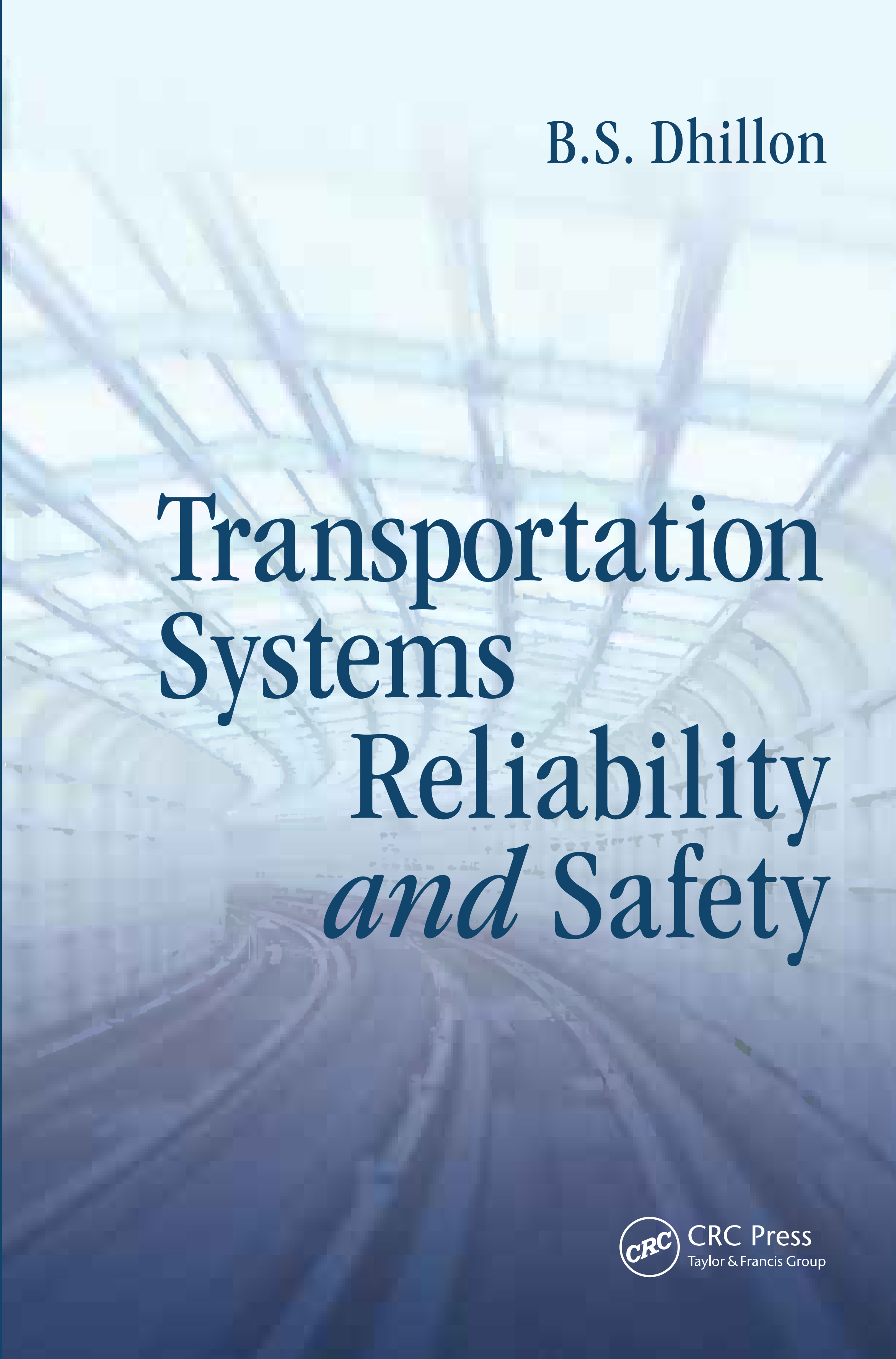

B.S. Dhillon

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This book is affectionately dedicated to my son, Mark.

Contents

Preface xiii
About the Author xvii

1. **Introduction** 1
  1.1 Background 1
  1.2 Transportation Systems Reliability and Safety Facts, Figures, and Examples 2
  1.3 Terms and Definitions 3
  1.4 Useful Sources for Obtaining Information on Transportation Systems Reliability and Safety 4
    1.4.1 Organizations 5
    1.4.2 Data Sources 5
    1.4.3 Standards 6
    1.4.4 Journals 7
    1.4.5 Conference Proceedings 8
    1.4.6 Books 8
  1.5 Scope of the Book 9
  References 10

2. **Reliability and Safety Mathematics** 13
  2.1 Introduction 13
  2.2 Arithmetic Mean, Mean Deviation, and Standard Deviation 13
    2.2.1 Arithmetic Mean 14
    2.2.2 Mean Deviation 14
    2.2.3 Standard Deviation 15
  2.3 Boolean Algebra Laws 16
  2.4 Probability Definition and Properties 17
  2.5 Useful Definitions 18
    2.5.1 Cumulative Distribution Function 18
    2.5.2 Probability Density Function 19
    2.5.3 Expected Value 19
    2.5.4 Variance 19
    2.5.5 Laplace Transform 19
    2.5.6 Laplace Transform: Final-Value Theorem 20
  2.6 Probability Distributions 21
    2.6.1 Binomial Distribution 22
    2.6.2 Exponential Distribution 22
    2.6.3 Rayleigh Distribution 23
    2.6.4 Weibull Distribution 24

2.6.5 Normal Distribution........24
2.6.6 General Distribution........25
2.7 Solving First-Order Differential Equations Using Laplace Transforms........25
References........28

3. **Reliability and Safety Basics**........29
3.1 Introduction........29
3.2 Bathtub Hazard Rate Curve........29
3.3 General Reliability-Related Formulas........31
3.3.1 Failure (or Probability) Density Function........31
3.3.2 Hazard Rate Function........31
3.3.3 General Reliability Function........32
3.3.4 Mean Time to Failure........33
3.4 Reliability Networks........34
3.4.1 Series Network........34
3.4.2 Parallel Network........37
3.4.3 *k*-out-of-*m* Network........39
3.4.4 Standby System........41
3.4.5 Bridge Network........43
3.5 Occupational Stressors and Reasons for Occurrence of Human Error........44
3.6 Human Error Consequences and Classifications........45
3.7 Safety and Engineers........46
3.8 Product Hazard Categories, Common Mechanical Injuries, and Common Causes of Work Injuries........47
3.9 Accident Causation Theories........49
3.9.1 Domino Accident Causation Theory........49
3.9.2 Human Factors Accident Causation Theory........51
References........52

4. **Methods for Performing Transportation System Reliability and Safety Analysis**........55
4.1 Introduction........55
4.2 Failure Modes and Effect Analysis (FMEA)........55
4.2.1 Failure Mode Effects and Criticality Analysis (FMECA)........56
4.3 Fault-Tree Analysis (FTA)........58
4.3.1 Probability Evaluation of Fault Trees........60
4.3.2 Fault-Tree Analysis (FTA) Benefits and Drawbacks........62
4.4 Markov Method........63
4.5 Hazards and Operability Analysis (HAZOP)........66
4.6 Interface Safety Analysis........67
4.7 Preliminary Hazard Analysis (PHA)........69
4.8 Job Safety Analysis........69

4.9 Technique of Operations Review (TOR) 70
References 71

5. Transportation System Failures 73
5.1 Introduction 73
5.2 Mechanical Failure–Related Aviation Accidents 73
5.3 Vehicle Failure Classifications and Defects in Vehicle Parts 75
5.4 Rail Defects and Weld Failures 77
5.5 Mechanical Failure–Related Delays in Commuter Rail Service 78
5.6 Rail and Road Tanker Failure Modes and Failure Consequences 79
5.7 Ship Failures and Their Causes 80
5.8 Failures in Marine Environments and Microanalysis Techniques for Failure Investigation 81
5.8.1 Differential Scanning Calorimetry 82
5.8.2 Thermomechanical Analysis 82
5.8.3 Fourier Transform Infrared Spectroscopy 82
5.8.4 Thermogravimetric Analysis 82
5.9 Submarine Ship–Control System Performance Monitoring and Fault Localization Process and Benefits 83
References 84

6. Transportation System Reliability Modeling 87
6.1 Introduction 87
6.2 Model I 87
6.3 Model II 90
6.4 Model III 93
6.5 Model IV 96
6.6 Model V 98
6.7 Model VI 101
6.8 Model VII 103
6.9 Model VIII 106
6.10 Model IX 109
6.11 Model X 112
6.12 Model XI 114
References 119

7. Rail Safety 121
7.1 Introduction 121
7.2 Causes of Railway-Related Accidents and Incidents, and Examples of the Causes of Specific Rail Accidents 121
7.3 General Classifications of Rail Accidents by Effects and Causes 123
7.4 Rail Derailment Accidents and Incidents and Their Causes 124

7.5 Telescoping-Related Railway Accidents 125
7.6 Railway Accidents in Selected Countries 126
  7.6.1 United Kingdom 126
  7.6.2 Ireland 126
  7.6.3 New Zealand 127
  7.6.4 Australia 127
7.7 Railroad Tank Car Safety 128
7.8 Light-Rail Transit-System Safety-Related Issues 129
7.9 Methods for Performing Rail Safety Analysis 130
  7.9.1 Fault-Tree Analysis 130
References 133

8. Truck and Bus Safety 135
8.1 Introduction 135
8.2 Top Truck and Bus Safety Issues 135
8.3 Truck Safety–Related Facts and Figures 136
8.4 Commonly Cited Truck Safety–Related Problems, Factors Associated with Heavy-Vehicle Accidents, and Safety Culture in the Trucking Industry 137
8.5 Safety-Related Truck Inspection Tips, Safety-Related Tips for Truck Drivers, and Recommendations for Improving Truck Safety 138
8.6 Bus and Coach Occupant Fatalities and Serious Injuries 140
8.7 Transit Bus Safety and Key Design-Related Safety Feature Areas 141
8.8 Vehicle Safety Data Sources 141
  8.8.1 National Highway Traffic Safety Administration 142
  8.8.2 National Transportation Safety Board (NTSB) 142
  8.8.3 Federal Highway Administration 143
  8.8.4 University of Michigan Transportation Research Institute (UMTRI) 143
  8.8.5 Insurance Industry 144
8.9 Motor Vehicle Traffic-Related Accidents in Selected Countries 144
References 145

9. Airline and Ship Safety 147
9.1 Introduction 147
9.2 United States Airline-Related Fatalities and Accident Rate 147
9.3 Aircraft Accidents during Flight Phases and Causes of Airplane Crashes 148
9.4 Worldwide Airline Accident Analysis 149
9.5 Air Safety–Related Regulatory Bodies and Their Responsibilities 150
  9.5.1 Federal Aviation Administration Responsibilities 150

9.5.2 National Transportation Safety Board Responsibilities 150
9.6 Aviation Recording and Reporting Systems 151
9.6.1 Accident Incident Data System (AIDS) 152
9.6.2 Aviation Safety Analysis System 152
9.6.3 Air Transportation Oversight System (ATOS) 153
9.6.4 Accident/Incident Reporting System 153
9.6.5 Aviation Safety Reporting System 154
9.6.6 ICAO ADREP System 154
9.7 Noteworthy Marine Accidents 154
9.7.1 *Estonia* Accident 155
9.7.2 *Derbyshire* Accident 155
9.7.3 *Prestige* Accident 155
9.7.4 *Herald of Free Enterprise* Accident 155
9.8 Ship Safety Assessment 156
9.9 Ship Port-Related Hazards 157
9.10 Global Maritime Distress Safety System (GMDSS) 158
References 159

10. Human Error in Rail and Road Transportation Systems 161
10.1 Introduction 161
10.2 Railway System Human Error–Related Facts, Figures, and Examples 161
10.3 Railway Operation–Related Typical Human Error Occurrence Areas 162
10.3.1 Train Speed 162
10.3.2 Signal Passing 163
10.3.3 Dispatching or Signaling 164
10.4 Railway Personnel Error-Prone Tasks and Error-Contributing Factors in Railway Operations 164
10.5 Checklist of Statements to Reduce Human Error in Railway Operations 165
10.6 Road Transportation Systems Human Error–Related Facts and Figures 166
10.7 Driver Error Classifications, Common Driver Errors, and Driver Error Ranking 167
10.8 Operational Influences on the Performance of Commercial Drivers 168
10.9 Bus Accidents and Bus Accident–Related Driver Errors in Selected Developing Countries 169
References 171

11. Human Error in Aviation and Sea Transportation Systems 173
11.1 Introduction 173
11.2 Aviation Transportation Systems 173

    - 11.2.1 Human Error in Aviation: Facts, Figures, and Examples ... 173
    - 11.2.2 Organizational Factors Related to Pilot Error in Commercial Aviation Accidents ... 174
    - 11.2.3 Flight-Crew Decision Error Contributory Factors ... 176
    - 11.2.4 Types of Pilot–Controller Communication Errors and Recommendations for Reducing Pilot–Controller Communication Errors ... 177
- 11.3 Sea Transportation Systems ... 178
    - 11.3.1 Human Error in Marine Shipping: Facts, Figures, and Examples ... 178
    - 11.3.2 Human Factors–Related Issues Facing the Marine Industrial Sector ... 179
    - 11.3.3 Impact of Reduced Manning on Shipping System Reliability and Approaches for Increasing Reliability ... 180
    - 11.3.4 Methods for Performing Risk Analysis in Marine Systems ... 181
- References ... 182

Bibliography: Literature on the Reliability and Safety of Transportation Systems ... 187

Preface

Each year, billions of dollars are spent globally to develop, manufacture, operate, and maintain transportation systems such as aircraft, ships, motor vehicles, and trains. These transportation systems' global impact is enormous. For example, the aviation industry's global economic impact (i.e., direct, indirect, induced, and catalytic) alone is estimated to be around USD 2,960 billion, equivalent to about 80% of the world gross domestic product (GDP).

Nonetheless, during the day-to-day use, thousands of lives are lost each year due to accidents, directly or indirectly, resulting from poor transportation system reliability and safety. For example, in the United States, automobile accidents alone result in around 42,000 deaths per year, costing billions of dollars to the U.S. economy each year.

Over the years, a large number of journal and conference proceedings articles on transportation systems' reliability and safety have appeared, but to the best of the author's knowledge, there is no book on the topic that covers recent developments in the area. This poses a substantial obstacle for information seekers on the subject, because they have to consult many different and diverse sources.

Thus, the main objective of this book is to eliminate the need to consult many different and diverse sources in obtaining desired information and to provide up-to-date information on the subject. The sources of most of the material presented are given in the reference section at the end of each chapter. These will be useful to readers if they desire to delve deeper into a specific area. The book contains a chapter on mathematical concepts and another chapter on reliability and safety basics considered useful to understand the contents of subsequent chapters. Furthermore, another chapter is devoted to methods considered useful to perform transportation system reliability and safety analysis.

The topics covered in the book are treated in such a manner that the reader will require no previous knowledge to understand the contents. At appropriate places, the book contains examples along with their solutions, and at the end of each chapter there are numerous problems to test the reader's comprehension in the area. An extensive list of publications dating from 1968 to recently, relating directly or indirectly on transportation systems reliability and safety, is provided at the end of this book to give readers a view of the intensity of developments in the area.

The book is composed of 11 chapters. Chapter 1 presents the need for and historical developments in transportation systems reliability and safety; transportation systems reliability and safety facts, figures, and examples; important terms and definitions; useful sources for obtaining information on transportation systems reliability and safety; and the scope of the book. Chapter 2 reviews mathematical concepts considered useful to understanding subsequent chapters. Some of the topics covered in the chapter are Boolean algebra laws, probability properties, probability distributions, and useful definitions.

Chapter 3 presents introductory aspects of reliability and safety. Chapter 4 presents a number of methods considered useful to perform transportation systems reliability and safety analysis. These methods are failure modes and effect analysis, fault-tree analysis, the Markov method, hazard and operability analysis, interface safety analysis, preliminary hazard analysis, job safety analysis, and technique of operations review.

Chapter 5 is devoted to transportation systems failures. Some of the topics covered in the chapter are mechanical failure–related aviation accidents, vehicle failure classifications, rail defects and weld failures, rail and road tanker failure modes and failure consequences, ship failures and their consequences, and failures in marine environments and microanalysis techniques for failure investigation. Chapter 6 presents a total of 11 mathematical models for performing various types of reliability analysis of transportation systems.

Chapters 7 and 8 are devoted to rail safety and to truck and bus safety, respectively. Chapter 7 covers topics such as causes of railway-related accidents and incidents, general classifications of rail accidents by effects and causes, rail derailment accidents and incidents and their causes, telescoping-related railway accidents, railway accidents in selected countries, railroad tank car safety, and methods for performing rail safety analysis. Some of the topics covered in Chapter 8 are top truck and bus safety issues, truck safety–related facts and figures, the most-cited truck safety–related problems, safety-related truck inspection tips, bus and coach occupant fatalities and serious injuries, transit bus safety and key design-related safety feature areas, and vehicle safety data sources.

Chapter 9 presents various important aspects of airline and ship safety, including U.S. airline–related fatalities and accident rates, aircraft accidents during flight phases and causes of airline crashes, world airline accident analysis, air safety–related regulatory bodies and their responsibilities, aviation recording and reporting systems, noteworthy marine accidents, ship safety assessment, and ship port-related hazards.

Chapter 10 is devoted to human error in rail and road transportation systems and covers topics such as railway system human error–related facts, figures, and examples; railway operation–related typical human error occurrence areas; railway personnel error-prone tasks and error-contributing factors in railway operations; road transportation systems human error–related facts and figures; driver error classifications and common driver errors; operational influences on the performance of commercial drivers; and bus accidents and bus accident–related driver errors in selected developing countries.

Finally, Chapter 11 presents various important aspects of human error in aviation and sea transportation systems. Some of the topics covered in the chapter are human error in aviation-related facts, figures, and examples; flight-crew decision error contributory factors; types of pilot–controller communication errors and recommendations for reducing pilot–controller communication errors; human error in shipping-related facts, figures, and examples; human factors–related issues facing the marine industrial sector; manning impact on shipping system reliability and approaches for reducing the manning impact on shipping system reliability; and methods for performing risk analysis in marine systems.

The book will be useful to many individuals, including reliability and safety professionals working in the transportation industry, transportation system administrators, transportation engineering undergraduate and graduate students, researchers and instructors in the area of transportation, and engineers at large.

The author is deeply indebted to many individuals, including friends, colleagues, and students for their invisible inputs. The invisible contributions of my children, Jasmine and Mark, are also appreciated. Last, but not least, I thank my boss, friend, and wife, Rosy for typing this entire book and for her timely help in proofreading.

B. S. Dhillon
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About the Author

Dr. B. S. Dhillon is a professor of engineering management in the Department of Mechanical Engineering at the University of Ottawa. He has served as a chairman/director of the Mechanical Engineering Department/Engineering Management Program for over 10 years at the same institution. He has published over 350 articles (203 journal and 147 conference proceedings) on reliability engineering, maintainability, safety, engineering management, etc. He is or has been on the editorial boards of 10 international scientific journals. In addition, Dr. Dhillon has written 37 books on various aspects of health care, engineering management, design, reliability, safety, and quality published by Wiley (1981), Van Nostrand (1982), Butterworth (1983), Marcel Dekker (1984), Pergamon (1986), etc. His books are being used in over 100 countries, and many of them are translated into languages such as German, Russian, Chinese, and Persian (Iranian). Dr. Dhillon is the founder of the statistical distribution named the Dhillon distribution by statistical researchers in their publications around the world.

He has served as general chairman of two international conferences on reliability and quality control held in Los Angeles and Paris in 1987. Professor Dhillon has also served as a consultant to various organizations and bodies and has many years of experience in the industrial sector. At the University of Ottawa, he has been teaching reliability, quality, engineering management, design, and related areas for over 30 years, and he has also lectured in more than 50 countries, including keynote addresses at various international scientific conferences held in North America, Europe, Asia, and Africa. In March 2004, Dr. Dhillon was a distinguished speaker at the Conference/Workshop on Surgical Errors (sponsored by the White House Health and Safety Committee and the Pentagon) held at Capitol Hill (One Constitution Avenue, Washington, D.C.).

Professor Dhillon attended the University of Wales, where he received a BS in electrical and electronic engineering and an MS in mechanical engineering. He received a PhD in industrial engineering from the University of Windsor.

1

Introduction

1.1 Background

Each year, billions of dollars are spent globally to develop, manufacture, operate, and maintain transportation systems such as aircraft, ships, trains, and motor vehicles. These systems carry billions of tons of goods and billions of passengers annually from one point to another point throughout the world. For example, as per the International Air Transportation Association (IATA), the world's 900 airlines with around 22,000 aircraft carry over 1.6 billion passengers for business and leisure travel each year, and over 40% of world trade of goods is carried by air [1–3].

During transportation systems' operation, thousands of lives are lost worldwide annually due to various types of failures and accidents. For example, in the United States alone, about 42,000 deaths occur each year due to automobile accidents on highways [4]. In terms of dollars and cents, the total cost of motor vehicle crashes to the United States economy in 1994 was estimated to be around $150 billion [4, 5].

Needless to say, transportation system failures have become an important issue worldwide because they can, directly or indirectly, impact the global economy and the environment as well as transportation reliability and safety. Although the history of reliability and safety fields may be traced back to 1940s and 1860s, respectively, the beginning of the serious thinking on transportation systems reliability and safety goes back only to the period around the 1970s. Since the late 1960s, a large number of publications directly or indirectly related to transportation system reliability or safety have appeared. A list of over 400 such publications is provided in the Appendix.

1.2 Transportation Systems Reliability and Safety Facts, Figures, and Examples

Some of the facts, figures, and examples directly or indirectly concerned with transportation systems reliability and safety are as follows:

- In 1990, there were approximately 40 million traffic injuries and about 1 million traffic deaths worldwide. According to the World Health Organization projection, the worldwide deaths from accidents will increase to about 2.3 million by 2020 [6, 7].
- As per Odero [8], the estimated yearly cost of world road crashes alone is in excess of $500 billion.
- In 1993, around 4,500 trucks in the United States were involved in an accident in which at least one fatality occurred [9].
- Decade breakdowns of worldwide fatal commercial aircraft accidents due to mechanical failure during the period 1950–2008 are as follows [10]:

  21 (1950–1959)

  20 (1960–1969)

  23 (1970–1979)

  21 (1980–1989)

  21 (1990–1999)

  28 (2000–2008)
- According to a Boeing study, the failure of the cockpit crew has been a contributing factor in over 73% of aircraft accidents worldwide [11, 12].
- A study of 666 railway-related accidents and incidents in Sweden during the period 1888–2000 grouped the causes for their occurrence under three categories: rolling stock (47%), rail and track (39%), and insufficient information (14%) [13].
- Human error contributes to 84%–88% of tanker accidents directly or indirectly [14, 15].
- In the United States, there were approximately 5400, 5100, 5000, 4000, 4500, 4900, and 5000 truck-related fatal crashes in 1980, 1986, 1989, 1992, 1995, 1997, and 2000, respectively [16].
- In 2004, approximately 53% of the accidents in railway switching yards (i.e., excluding highway–rail-crossing train accidents) in the United States were due to human factors–related causes [17].
- During the period 1993–2003, the fatal crash rate for large trucks in the United States declined by 20% [16].

- During the period 1983–1996, there were 371 major airline crashes, 29,798 general aviation crashes, and 1,735 commuter/air taxi crashes [18] worldwide.
- Bus and coach occupant fatalities in the United Kingdom in 1966, 1970, 1975, 1980, 1985, 1990, and 1991 were 76, 74, 115, 29, 32, 19, and 25, respectively [19].
- Over 80% of marine accidents are due to or influenced by human and organization-related factors [20, 21].
- In 2003, out of 4,986 fatalities that occurred from crashes involving large trucks in the United States, 14% were large-truck occupants, 78% were occupants of another vehicle, and 8% were nonoccupants [16, 22].
- In 1979, a DC-10 aircraft accident due to maintenance personnel following improper maintenance procedures resulted in 272 fatalities [23].
- In 1974, Turkish Airlines Flight 981 (aircraft type: McDonnell Douglas DC-10-10) crashed due to cargo hatch failure and control cable failures, causing 346 fatalities [24].
- A study conducted by the National Aeronautics and Space Administration (NASA) reported that over 70% of airline accidents, since the introduction of turbojet aircraft in the later years of the 1950s, involved some degree of human error [25].
- In 2002, an Amtrak auto train derailed due to malfunctioning breaks and poor track maintenance near Crescent City, Florida, causing 4 fatalities and 142 injuries [26].
- In 1994, US Air Flight 427 (aircraft type: Boeing 737-387) crashed due to rudder device malfunction, causing 132 fatalities [27].
- In 2004, a Union Pacific Railroad train failed to stop at a signal and collided with another train in Macdona, Texas, resulting in 3 fatalities and 51 injuries [28].
- In 1991, United Airlines Flight 585 (aircraft type: Boeing 737-291) crashed due to rudder device malfunction, causing 25 fatalities [29].

1.3 Terms and Definitions

There is a large number of terms and definitions used in the area of transportation systems reliability and safety. Some of these are presented as follows [30–34]:

- **Reliability.** The probability that an item will carry out its stated mission satisfactorily for the specified time period when used according to the specified conditions.
- **Safety.** The conservation of human life and the prevention of damage to items as per mission-specified requirements.

- **Transportation system.** A facility consisting of the means and equipment necessary for the movement of passengers or goods.
- **Accident.** An unplanned and undesired event.
- **Failure.** The inability of an item to function within the stated guidelines.
- **Human error.** The failure to perform a stated task (or the performance of a forbidden action) that could result in disruption of scheduled operations or result in damage to equipment and property.
- **Mission time.** The element of uptime that is required to carry out a specified mission profile.
- **Redundancy.** The existence of more than one means for carrying out a stated function.
- **Human-error consequence.** An undesired consequence of human failure.
- **Safety management.** The accomplishment of safety through the effort of others (i.e., people).
- **Reliability model.** A model for assessing, predicting, or estimating reliability.
- **Unsafe condition.** Any condition, under the right set of conditions, that will lead to an accident.
- **Unsafe act.** An act that is not safe for the employee or an individual.
- **Safeguard.** A barrier guard, device, or procedure developed for the protection of humans.
- **Failure mode.** The abnormality of items/systems performance that causes the item/system to be considered as failed.
- **Injury.** A wound or other specific damage.
- **Hazard control.** A means of reducing the risk of exposure to a perceived hazard.
- **Human reliability.** The probability of accomplishing a task successfully by humans at any required stage in system operation. In some cases, the task must be accomplished within a stated time limit.
- **Continuous task.** A task that involves some kind of tracking activity (e.g., monitoring a changing condition).

1.4 Useful Sources for Obtaining Information on Transportation Systems Reliability and Safety

There are many sources to obtain information, directly or indirectly, concerned with transportation systems reliability and safety. Some of the sources considered most useful are presented below under a number of distinct categories.

1.4.1 Organizations

- Reliability Society, IEEE, P.O. Box 1331, Piscataway, New Jersey
- American Society of Safety Engineers, 1800 East Oakton St., Des Plaines, Illinois
- Transportation Research Board, 2101 Constitution Avenue, NW, Washington, D.C.
- Federal Rail Road Administration, 4601 N. Fairfax Drive, Suite 1100, Arlington, Virginia
- Transportation Safety Board of Canada, 330 Spark Street, Ottawa, Ontario, Canada
- Marine Directorate, Department of Transport, 76 Marsham Street, London, U.K.
- International Civil Aviation Organization, 999 University Street, Montreal, Quebec, Canada
- Word Safety Organization, P.O. Box No. 1, Lalong Laan Building, Pasay City, Metro Manila, The Philippines
- National Safety Council, 444 North Michigan Avenue, Chicago, Illinois
- U.S. Coast Guard, 2100 Second Street, SW, Washington, D.C.
- Airplane Safety Engineering Department, Boeing Commercial Airline Group, The Boeing Company, 7755 E. Marginal Way South, Seattle, Washington
- System Safety Society, 14252 Culver Drive, Suite A-261, Irvine, California
- British Safety Council, 62 Chancellors Road, London, U.K.
- Civil Aviation Safety Authority, North Bourne Avenue and Barry Drive Intersection, Canberra, Australia
- National Research Council, 2101 Constitution Avenue, NW, Washington, D.C.
- Occupational Safety and Health Administration, U.S. Department of Labor, 200 Constitution Avenue, Washington, D.C.

1.4.2 Data Sources

- Government Industry Data Exchange Program (GIDEP), GIDEP Operations Center, U.S. Department of the Navy, Corona, California
- Reliability Analysis Center, Rome Air Development Center (RADC), Griffis Air Force Base, New York, New York 13441-5700

- Defense Technical Information Center, DTIC-FDAC, 8725 John J. Kingman Road, Suite 0944, Fort Belvoir, Virginia 22060-6218
- National Aeronautics and Space Administration (NASA) Parts Reliability Information Center, George C. Marshall Space Flight Center, Huntsville, Alabama 35812
- NASA Aviation Safety Reporting System, P.O. Box 189, Moffett Field, California
- American National Standards Institute (ANSI), 11 W. 42nd St., New York, New York 10036
- National Maritime Safety Incident Reporting System, Maritime Administration, Washington, D.C.
- Gertman, D. I., and Blackman, H. S., *Human Reliability and Safety Analysis Data Handbook*, John Wiley and Sons, New York, 1994.
- Boff, K. R., and Lincoln, J. E., *Engineering Data Compendium: Human Perception and Performance*, Vol. 1–3, 1988. Available from the Armstrong Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio.
- Space Documentation Service, European Space Agency, Via Galileo Galilei, Frascati 00044, Italy
- National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia

1.4.3 Standards

- MIL-STD-785, Reliability Program for Systems and Equipment, Development and Production, Department of Defense, Washington, D.C.
- MIL-STD-721, Definitions of Terms for Reliability and Maintainability, Department of Defense, Washington, D.C.
- SAE ARD 50010, Recommended Reliability, Maintainability, and Supportability (RMS) Terms and Parameters, Society of Automotive Engineers (SAE), Warrendale, Pennsylvania
- MIL-STD-1908, Definitions of Human Factors Terms, Department of Defense, Washington, D.C.
- MIL-HDBK-217, Reliability Prediction of Electronic Equipment, Department of Defense, Washington, D.C.
- MIL-STD-58077, Safety Engineering of Aircraft System, Associated Subsystem and Equipment: General Requirements, Department of Defense, Washington, D.C.
- MIL-STD-882, Systems Safety Program for System and Associated Subsystem and Equipment-Requirements, Department of Defense, Washington, D.C.

- DEF-STD-00-55-1, Requirements for Safety-Related Software in Defense Equipment, Department of Defense, Washington, D.C.
- IEC 60950, Safety of Information Technology Equipment, International Electro-Technical Commission, Geneva, Switzerland, 1999.
- MIL-STD-1629, Procedures for Performing Failure Mode, Effects and Criticality Analysis, Department of Defense, Washington, D.C.
- IEC 61508 SET, Functional Safety of Electrical/Electronic/Programmable Electronic Safety-Related Systems, Parts 1–7, International Electro-Technical Commission, Geneva, Switzerland, 2000.
- MIL-STD-756, Reliability Modeling and Prediction, Department of Defense, Washington, D.C.
- MIL-STD-2155, Failure Reporting, Analysis, and Corrective Action (FRACAS), Department of Defense, Washington, D.C.
- MIL-HDBK-338, Electronics Reliability Design Handbook, Department of Defense, Washington, D.C.
- MIL-STD-790, Reliability Assurance Program for Electronic Parts Specifications, Department of Defense, Washington, D.C.

1.4.4 Journals

- *IEEE Transactions on Reliability*
- *International Journal of Reliability, Quality, and Safety Engineering*
- *Microelectronics and Reliability*
- *Reliability Engineering and System Safety*
- *Journal of Safety Research*
- *Safety Management Journal*
- *Accident Analysis and Prevention*
- *National Safety News*
- *Naval Engineers Journal*
- *Marine and Maritime*
- *Transportation Research Record*
- *Railway Age*
- *Professional Engineering*
- *Safety Science*
- *Journal of Marine Science and Technology*
- *Engineering Failure Analysis*
- *Public Roads*
- *Marine Technology*

- *SAE (Society of Automotive Engineers) Transactions*
- *Transportation Quarterly*
- *International Journal of Heavy Vehicle Systems*
- *Ergonomics*

1.4.5 Conference Proceedings

- Proceedings of the Annual Reliability and Maintainability Symposium
- Proceedings of the System Safety Conferences
- Proceedings of the ISSAT International Conferences on Reliability and Quality in Design
- Proceedings of the International Conferences on Probabilistic Safety Assessment and Management
- Proceedings of the European Conferences on Safety and Reliability
- Proceedings of the International Conference on Rail Transport Systems, 1994.
- Proceedings of the Human Factors and Ergonomics Society Annual Meetings
- Proceedings of the International Conferences on Computer Aided Design, Manufacture, and Operation in the Railway and Other Mass Transit Systems
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1.5 Scope of the Book

Each year a vast sum of money is spent around the world to develop, manufacture, operate, and maintain transportation systems such as aircraft, trains, motor vehicles, and ships. During their day-to-day use, thousands of lives are lost annually due to accidents resulting, directly or indirectly, from poor transportation system reliability and safety, costing billions of dollars to the global economy. Over the years, a large number of journal and conference proceedings articles, technical reports, etc., on the reliability and safety of transportation systems have appeared in the literature. However, to the best of the author's knowledge, there is no book on the topic that covers recent developments in this area. This is a significant impediment to information seekers on the subject, because they have to consult many different and diverse sources.

Thus, the main objectives of this book are (a) to eliminate the need for professionals concerned with transportation system reliability and safety to consult many different and diverse sources in obtaining desired information and (b) to provide up-to-date information on the subject. The book will be useful to many individuals, including reliability and safety professionals working in the transportation industry, transportation system administrators, transportation engineering undergraduate and graduate students, researchers and instructors in the area of transportation, and engineers-at-large.

Problems

1. Define the following terms:
    a. Transportation system
    b. Safety
    c. Reliability
2. Write an essay on the reliability and safety of transportation systems.
3. List at least five useful sources for obtaining information related to the reliability and safety of transportation systems.
4. List six important facts and figures concerning the reliability and safety of transportation systems.
5. What is the difference between the terms *unsafe act* and *unsafe condition*?
6. List six important journals for obtaining information related to the reliability and safety of transportation systems.
7. Define the following three terms:
    a. Accident
    b. Failure
    c. Mission time
8. List at least four books considered important for obtaining information related to the reliability and safety of transportation systems.
9. What is the difference between the terms *human reliability* and *human error*?
10. List seven important organizations for obtaining information related to the reliability and safety of transportation systems.

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2

Reliability and Safety Mathematics

2.1 Introduction

Just like in the development of other areas of science and engineering, mathematics has also played an important role in the development of reliability and safety fields. Although the origin of the word *mathematics* may be traced back to the ancient Greek word *mathema*, which means “science, knowledge, or learning,” the history of our current number symbols, often referred to as a “Hindu-Arabic numeral system,” goes back to around 250 b.c., to the stone columns erected by the Scythian emperor of India named Asoka [1].

The history of probability goes back to the gambler’s manual written by Girolamo Cardano (1501–1576), in which he considered some interesting issues on probability [1, 2]. However, Pierre Fermat (1601–1665) and Blaise Pascal (1623–1662) were the first two individuals who solved correctly and independently the problem of dividing the winnings in a game of chance. Pierre Fermat also introduced the idea of “differentiation.”

Laplace transforms, often used to find solutions to a set of differential equations, were developed by Pierre-Simon Laplace (1749–1827). Additional information on the history of mathematics, including probability, is available in the literature [1, 2]. This chapter presents various mathematical concepts considered useful to understand subsequent chapters of this book.

2.2 Arithmetic Mean, Mean Deviation, and Standard Deviation

A set of given transportation reliability or safety data is useful only if it is analyzed effectively. More specifically, there are certain characteristics of the data that are useful to describe the nature of a given data set, thus enabling better decisions related to the data. This section presents three statistical measures considered useful in the area of transportation system reliability and safety.

2.2.1 Arithmetic Mean

Often, the arithmetic mean is simply referred to as *mean* and is expressed by

$$m = \frac{\sum_{j=1}^{n} \mathrm{DV}_j}{n} \tag{2.1}$$

where

m = mean value

n = number of data values

DV_j = data value j, for $j = 1,2,3,\ldots,n$

Example 2.1

Assume that the inspection department of an organization involved in the manufacture of systems for use in the area of transportation inspected ten identical systems and discovered 5, 4, 6, 7, 9, 10, 3, 2, 8, and 1 defects in each system. Calculate the average number of defects per system (i.e., arithmetic mean).

By inserting the specified data values into Equation (2.1), we obtain

$$\begin{aligned} m &= \frac{5+4+6+7+9+10+3+2+8+1}{10} \\ &= 5.5 \end{aligned}$$

Thus, the average number of defects per system is 5.5. In other words, the arithmetic mean of the given data set is 5.5.

2.2.2 Mean Deviation

This is a commonly used measure of dispersion, which indicates the degree to which given data tend to spread about a mean value. Mean deviation is expressed by

$$\mathrm{MD} = \frac{\sum_{j=1}^{n} \left|\mathrm{DV}_j - m\right|}{n} \tag{2.2}$$

where

MD = mean deviation

n = number of data values

DV_j = data value j, for $j = 1,2,3,\ldots,n$

m = mean value of the given data set

$\left|\mathrm{DV}_j - m\right|$ = absolute value of the deviation of DV_j from m

Example 2.2

Calculate the mean deviation of the data set provided in Example 2.1.

Using the data set from Example 2.1 and the calculated mean value (i.e., $m = 5.5$ defects/system) in Equation (2.2), we get

$$\begin{aligned} \text{MD} &= \frac{\begin{array}{c}\left[|5-5.5|+|4-5.5|+|6-5.5|+|7-5.5|+|9-5.5|+\right.\\ \left.|10-5.5|+|3-5.5|+|2-5.5|+|8-5.5|+|1-5.5|\right]\end{array}}{10} \\ &= \frac{0.5+1.5+0.5+1.5+3.5+4.5+2.5+3.5+2.5+4.5}{10} \\ &= 2.5 \end{aligned}$$

Thus, the mean deviation of the Example 2.1 data set is 2.5.

2.2.3 Standard Deviation

Standard deviation is a widely used measure of dispersion of data in a given data set about the mean and is expressed by

$$\sigma = \left[\frac{\sum_{j=1}^{n}(DV_j - \mu)^2}{n}\right]^{1/2} \tag{2.3}$$

where

σ = standard deviation

μ = mean value

n = number of data values

DV_j = data value j, for $j = 1,2,3,\ldots,n$

The following three properties of the standard deviation are associated with the widely used normal distribution discussed later in the chapter:

- 99.73% of the all data values are included between $\mu - 3\sigma$ and $\mu + 3\sigma$.
- 95.45% of the all data values are included between $\mu - 2\sigma$ and $\mu + 2\sigma$.
- 68.27% of the all data values are included between $\mu - \sigma$ and $\mu + \sigma$.

Example 2.3

Calculate the standard deviation of the data set given in Example 2.1

Using the Example 2.1 data set and the calculated mean value (i.e., $m = \mu = 5.5$) in Equation (2.3), we get

$$\alpha = \left[\frac{\begin{array}{l}(5-5.5)^2+(4-5.5)^2+(6-5.5)^2+(7-5.5)^2+(9-5.5)^2+\\(10-5.5)^2+(3-5.5)^2+(2-5.5)^2+(8-5.5)^2+(1-5.5)^2\end{array}}{10}\right]^{1/2}$$

$$= \frac{0.25+2.25+0.25+2.25+12.25+20.25+6.25+12.25+6.25+20.25}{10}$$

$$= 2.87$$

Thus, the standard deviation of the Example 2.1 data set is 2.87.

2.3 Boolean Algebra Laws

Boolean algebra plays an important role in various types of transportation system reliability and safety studies and is named after George Boole (1813–1864), a mathematician. Some of the Boolean algebra laws are as follows [3, 4]:

- **Commutative Law:**

$$X + Y = Y + X \tag{2.4}$$

where
X is an arbitrary set or event.
Y is an arbitrary set or event.
+ denotes the union of sets.

$$X.Y = Y.X \tag{2.5}$$

where
Dot (.) denotes the intersection of sets. Note that Equation (2.5) sometimes is written without the dot (e.g., XY), but it still conveys the same meaning.

- **Associative Law:**

$$(XY)Z = X(YZ) \tag{2.6}$$

where
Z is an arbitrary set or event.

$$(X + Y) + Z = X + (Y + Z) \tag{2.7}$$

- **Idempotent Law:**

$$X + X = X \tag{2.8}$$

$$XX = X \tag{2.9}$$

- **Absorption Law:**

$$X(X + Y) = X \tag{2.10}$$

$$X + (XY) = X \tag{2.11}$$

- **Distributive Law:**

$$(X + Y)(X + Z) = X + YZ \tag{2.12}$$

$$X(Y + Z) = XY + XZ \tag{2.13}$$

2.4 Probability Definition and Properties

Probability is defined as follows [5]:

$$P(Y) = \lim_{m\to\infty}\left[\frac{M}{m}\right] \tag{2.14}$$

where

$P(Y)$ = probability of occurrence of event Y

M = number of times event Y occurs in the m repeated experiments

Some of the probability properties are as follows [5, 6].

- The probability of occurrence of event, say X, is

$$0 \leq P(X) \geq 1 \tag{2.15}$$

- Probability of the sample space S is

$$P(S) = 1 \tag{2.16}$$

- Probability of the negation of the sample space S is

$$P\left(\bar{S}\right) = 0 \tag{2.17}$$

where

$\bar{S}$ = negation of the sample space S

- The probability of occurrence and nonoccurrence of an event, say X, is always

$$P(X) + P(\bar{X}) = 1 \tag{2.18}$$

where

$P(\underline{X})$ = probability of occurrence of event X

$P(X)$= probability of nonoccurrence of event X

- The probability of the union of *k* independent events is

$$P(X_1 + X_2 + \ldots + X_k) = 1 - \prod_{i=1}^{k} \left(1 - P\left(X_i\right)\right) \tag{2.19}$$

where

$P(X_i)$ = probability of occurrence of event X_i for $i = 1,2,3,\ldots,k$

- The probability of the union of *k* mutually exclusive events is

$$P(X_1 + X_2 + \ldots + X_k) = \sum_{i=1}^{k} P(X_i) \tag{2.20}$$

- The probability of an intersection of *k* independent events is

$$P(X_1X_2X_3\ldots X_k) = P(X_1)P(X_2)P(X_3)\ldots P(X_k) \tag{2.21}$$

2.5 Useful Definitions

This section presents a number of mathematical definitions considered useful to conduct various types of transportation system reliability and safety studies.

2.5.1 Cumulative Distribution Function

For continuous random variables, this is defined by [5]

$$F(t) = \int_{-\infty}^{t} f(x)dx \tag{2.22}$$

where

t = time

$F(t)$ = cumulative distribution function

$f(t)$ = probability density function

For $t = \infty$, Equation (2.22) yields

$$F(t) = \int_{-\infty}^{\infty} f(x)dx = 1 \tag{2.23}$$

It simply means that the total area under the probability density curve is equal to unity.

2.5.2 Probability Density Function

This is defined by [5, 7]

$$f(t) = \frac{dF(t)}{dt} \tag{2.24}$$

2.5.3 Expected Value

The expected value, $E(t)$, of a continuous random variable is defined by

$$E(t) = m = \int_{-\infty}^{\infty} t f(t) dt \tag{2.25}$$

where

$E(t)$ = expected value of the continuous random variable t

m = mean value

Similarly, the expected value, $E(t)$, of a discrete random variable t is given by

$$E(t) = \sum_{i=1}^{n} t_i f(t_i) \tag{2.26}$$

where

n = number of discrete values of the random variable t

2.5.4 Variance

The variance, $\sigma^2(t)$, of a random variable t is defined by

$$\sigma^2(t) = E(t^2) - [E(t)]^2 \tag{2.27}$$

or

$$\sigma^2(t) = \int_{0}^{\infty} t^2 f(t) dt - m^2 \tag{2.28}$$

where

m = mean value

2.5.5 Laplace Transform

The Laplace transform of the function $f(t)$ is defined by

$$f(s) = \int_{0}^{\infty} f(t) e^{-st} dt \tag{2.29}$$

where
s = Laplace transform variable
t = time variable
$f(s)$ = Laplace transform of $f(t)$

Example 2.4

Obtain the Laplace transform of the function

$$f(t) = e^{-\lambda t} \tag{2.30}$$

where
λ = a constant
By substituting Equation (2.30) into Equation (2.29), we get

$$f(s) = \int_0^\infty e^{-\lambda t} e^{-st} dt$$

$$= \int_0^\infty e^{-(s+\lambda)t} dt \tag{2.31}$$

$$= \frac{1}{s+\lambda}$$

Laplace transforms of some frequently occurring functions used in the analysis of transportation system reliability and safety are presented in Table 2.1 [8, 9].

2.5.6 Laplace Transform: Final-Value Theorem

If the following limits exist, then the final-value theorem may be expressed as

$$\lim_{t\to\infty} f(t) = \lim_{s\to 0}\left[sf(s)\right] \tag{2.32}$$

Example 2.5

Prove by using the following equation that the left-hand side of Equation (2.32) is equal to its right-hand side:

$$f(t) = \frac{\theta}{(\alpha+\theta)} + \frac{\alpha}{(\alpha+\theta)} e^{-(\alpha+\theta)t} \tag{2.33}$$

where
α and θ are constants.
By substituting Equation (2.33) into the left-hand side of Equation (2.32), we get

TABLE 2.1

Laplace Transforms of Some Frequently Occurring Functions in Transportation System Reliability and Safety Work

$f(t)$	$f(s)$
C, a constant	$\frac{c}{s}$
$e^{-\lambda t}$	$\frac{1}{s+\lambda}$
$\frac{df(t)}{dt}$	$s\,f(s) - f(0)$
t^m, for $m = 0,1,2,3,\ldots$	$\frac{m!}{s^{m+1}}$
$\theta_1 f_1(t) + \theta_2 f_2(t)$	$\theta_1 f_1(s) + \theta_2 f_2(s)$
$te^{-\lambda t}$	$\frac{1}{(s+\lambda)^2}$
$t\,f(t)$	$-\frac{df(s)}{ds}$

Source: [8, 9].

$$\lim_{t\to\infty}\left[\frac{\theta}{(\alpha+\theta}+\frac{\alpha}{(\alpha+\theta)}e^{-(\alpha+\theta)t}\right]=\frac{\theta}{(\alpha+\theta)} \tag{2.34}$$

Using Table 2.1 and Equation (2.33), we get

$$f(s)=\frac{\theta}{s(\alpha+\theta)}+\frac{\alpha}{(\alpha+\theta)}.\frac{1}{(s+\alpha+\theta)} \tag{2.35}$$

By substituting Equation (2.35) into the right-hand side of Equation (2.32), we get

$$\lim_{s\to 0}\left[\frac{s\theta}{s(\alpha+\theta)}+\frac{s\alpha}{(\alpha+\theta)}.\frac{1}{(s+\alpha+\theta)}\right]=\frac{\theta}{(\alpha+\theta)} \tag{2.36}$$

The right-hand sides of Equations (2.34) and (2.36) are the same. Thus, it proves that the left-hand side of Equation (2.32) is equal to its right-hand side.

2.6 Probability Distributions

This section presents a number of probability distributions considered useful to perform various types of studies in the area of transportation system reliability and safety [10].

2.6.1 Binomial Distribution

This discrete random variable distribution is used in circumstances where one is concerned with the probabilities of outcome such as the number of occurrences (e.g., failures) in a sequence of m trials. More specifically, each trial has two possible outcomes (e.g., success or failure), but the probability of each trial remains unchanged or constant.

This distribution is also known as the Bernoulli distribution, after Jakob Bernoulli (1654–1705) [1]. The binomial probability density function, $f(x)$, is defined by

$$f(x) = \binom{m}{i} p^x q^{m-x}, \text{for } x = 0,1,2,\ldots,m \tag{2.37}$$

where

$$\binom{m}{i} = \frac{m!}{i!(m-i)!}$$

x = number of nonoccurrences (e.g., failures) in m trials
p = single trial probability of occurrence (e.g., success)
q = single trial probability of nonoccurrence (e.g., failure)

The cumulative distribution function is given by

$$F(x) = \sum_{i=0}^{x} \binom{m}{i} p^i q^{m-i} \tag{2.38}$$

where

$F(x)$ = cumulative distribution function or the probability of x or fewer nonoccurrences (e.g., failures) in m trials

Using Equations (2.26) and (2.37), the expected value or the mean of the distribution is

$$E(x) = mp \tag{2.39}$$

2.6.2 Exponential Distribution

The exponential distribution is a continuous random variable distribution that is widely used in the industrial sector, particularly in performing reliability studies [11]. The probability density function of the distribution is defined by

$$f(t) = \lambda e^{-\lambda t}, t \geq 0, \lambda \rangle 0 \tag{2.40}$$

where

$f(t)$ = probability density function
t = time

λ = distribution parameter

By inserting Equation (2.40) into Equation (2.22), we get the following expression for the cumulative distribution function:

$$F(t) = 1 - e^{-\lambda t} \tag{2.41}$$

Using Equations (2.40) and (2.25), we obtain the following expression for the distribution mean value:

$$E(t) = m = \frac{1}{\lambda} \tag{2.42}$$

where

m = mean value

2.6.3 Rayleigh Distribution

This continuous random variable distribution is named after John Rayleigh (1842–1919), its originator [1]. The probability density function of the distribution is defined by

$$f(t) = \left(\frac{2}{\theta^2}\right) t e^{-\left(\frac{t}{\theta}\right)^2}, t \geq 0, \theta \rangle 0 \tag{2.43}$$

where

θ = distribution parameter

Substituting Equation (2.43) into Equation (2.22), we obtain the following cumulative distribution function:

$$F(t) = 1 - e^{-\left(\frac{t}{\theta}\right)^2} \tag{2.44}$$

Using Equation (2.43) and Equation (2.25), we get the following expression for the distribution mean value:

$$E(t) = m = \theta\Gamma\left(\frac{3}{2}\right) \tag{2.45}$$

where

$\Gamma(.)$ = gamma function, which is defined by

$$\Gamma(y) = \int_0^\infty t^{y-1} e^{-t} dt, \quad \text{for } y > 0 \tag{2.46}$$

2.6.4 Weibull Distribution

This continuous random variable distribution is named after W. Weibull, a Swedish mechanical engineering professor, who developed it in the early 1950s [12]. The distribution can be used to represent many different physical phenomena, and its probability density function is defined by

$$f(t) = \frac{bt^{b-1}}{\beta^b} e^{-\left(\frac{t}{\beta}\right)^b}, t \geq 0, \beta \rangle 0, b \rangle 0 \tag{2.47}$$

where β and b are the distribution scale and shape parameters, respectively.

By substituting Equation (2.47), into Equation (2.22), we get the following cumulative distribution function

$$\mathrm{F(t)=1\text{-}e}^{-\left(\frac{t}{\beta}\right)^b} \tag{2.48}$$

It is to be noted that exponential and Rayleigh distributions are the special cases of this distribution for $b = 1$ and $b = 2$, respectively.

Using Equation (2.47) and Equation (2.25), we obtain the following equations for the distribution mean value:

$$E(t) = m = \beta\Gamma\left(1 + \frac{1}{b}\right) \tag{2.49}$$

2.6.5 Normal Distribution

The normal distribution is a widely used continuous random variable distribution, and sometimes it is called the Gaussian distribution after Carl Friedrich Gauss (1777–1855), a German mathematician. The probability density function of the distribution is expressed by

$$f(t) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(t-\mu)^2}{2\sigma^2}\right], -\infty < t < +\infty \tag{2.50}$$

where μ and σ are the distribution parameters (i.e., mean and standard deviation, respectively).

Using Equations (2.22) and (2.50), we obtain the following cumulative distribution function:

$$F(t) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{t} \exp\left[-\frac{(t-\mu)^2}{2\sigma^2}\right] dx \tag{2.51}$$

Substituting Equation (2.50) into Equation (2.25) yields the following equation for the distribution mean value:

$$\begin{aligned} E(t) = m &= \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{\infty} t \exp\left[-\frac{(t-\mu)^2}{2\sigma^2}\right] dt \\ &= \mu \end{aligned} \tag{2.52}$$

2.6.6 General Distribution

This probability distribution can be used to represent the entire bathtub hazard rate curve presented in Chapter 3. The probability density function of the distribution is defined by [13, 14]

$$f(t) = \left[c\lambda\theta t^{\theta-1} + (1-c)bt^{b-1}\alpha e^{\alpha t^b}\right]\left[\exp[-c\lambda t^{\theta} - (1-c)(e^{\alpha t^b} - 1)\right] \tag{2.53}$$

for $0 \le c \le 1$ and $\lambda, \theta, b, \alpha > 0$

where

t = time

λ and α = distribution scale parameters

θ and b = distribution shape parameters

By substituting Equation (2.53) into Equation (2.22), we obtain the following cumulative distribution function:

$$F(t) = 1 - \exp\left[-c\lambda t^{\theta} - (1-c)(e^{\alpha t^b} - 1)\right] \tag{2.54}$$

The following probability distributions are the special cases of this distribution:

- Weibull distribution; for $c = 1$
- Makeham distribution; for $\theta = 1$, $b = 1$
- Extreme value distribution; for $c = 0$, $b = 1$
- Bathtub hazard rate curve; for $b = 1$, $\theta = 0.5$
- Rayleigh distribution; for $c = 1$, $\theta = 2$
- Exponential distribution; for $c = 1$, $\theta = 1$

2.7 Solving First-Order Differential Equations Using Laplace Transforms

Often, Laplace transforms are used to find solutions to linear first-order differential equations, particularly when a set of linear first order differential equations is involved. An example presented below demonstrates the finding of solutions to a set of differential equations describing a transportation system.

Example 2.6

Assume that a transportation system can be in either of the three states: operating normally, failed safely, or failed unsafely. The following three differential equations describe each of these transportation system states:

$$\frac{dP_0(t)}{dt} + (\lambda_s + \lambda_{us})P_0(t) = 0 \tag{2.55}$$

$$\frac{dP_1(t)}{dt} - \lambda_{us}P_0(t) = 0 \tag{2.56}$$

$$\frac{dP_2(t)}{dt} - \lambda_s P_0(t) = 0 \tag{2.57}$$

where

$P_j(t)$ = probability that the transportation system is in state j at time t, for $j = 0$ (operating normally), $j = 1$ (failed unsafely), and $j = 2$ (failed safely)

λ_s = transportation system constant safe failure rate

λ_{us} = transportation system constant unsafe failure rate

At time $t = 0$, $P_0(0) = 1$, $P_1(0) = 0$, and $P_2(0) = 0$.

Solve Equations (2.55)–(2.57) by using Laplace transforms.

Using Table 2.1, the specified initial conditions, and Equations (2.55)–(2.57), we get

$$sP_0(s) + (\lambda_s + \lambda_{us})P_0(s) = 1 \tag{2.58}$$

$$sP_1(s) - \lambda_{us}P_0(s) = 0 \tag{2.59}$$

$$sP_2(s) - \lambda_s P_0(s) = 0 \tag{2.60}$$

Solving Equations (2.58)–(2.60), we obtain

$$P_0(s) = \frac{1}{(s + \lambda_s + \lambda_{us})} \tag{2.61}$$

$$P_1(s) = \frac{\lambda_{us}}{s(s + \lambda_s + \lambda_{us})} \tag{2.62}$$

$$P_2(s) = \frac{\lambda_s}{s(s + \lambda_s + \lambda_{us})} \tag{2.63}$$

Taking the inverse Laplace transforms of Equations (2.61)–(2.63), we get

$$P_0(t) = e^{-(\lambda_s + \lambda_{us})t} \tag{2.64}$$

$$P_1(t) = \frac{\lambda_{us}}{(\lambda_s + \lambda_{us})}\left[1 - e^{-(\lambda_s + \lambda_{us})t}\right] \tag{2.65}$$

$$P_2(t) = \frac{\lambda_s}{(\lambda_s + \lambda_{us})}\left[1 - e^{-(\lambda_s + \lambda_{us})t}\right] \tag{2.66}$$

Thus, Equations (2.64–2.66) are the solutions to Equations (2.55–2.57).

Problems

1. Write an essay on the historical developments in the area of mathematics.
2. A transportation equipment manufacturing company's inspection department inspected eight identical systems and discovered 15, 2, 5, 8, 9, 3, 4, and 6 defects in each system. Calculate the average number of defects per system (i.e., arithmetic mean).
3. Define the following two terms:
   a. Mean deviation
   b. Standard deviation
4. Describe the following three terms:
   a. Associative law
   b. Idempotent law
   c. Absorption law
5. Write down six properties of probability.
6. Define the following three terms:
   a. Cumulative distribution function
   b. Expected value
   c. Laplace transform
7. What are the special-case probability distributions of the Weibull distribution?
8. Prove that the sum of Equations (2.64)–(2.66) is equal to unity.
9. Prove that the mean of the Rayleigh distribution is given by Equation (2.45).
10. What are the special-case probability distributions of the general distribution? Define the probability density function of the general distribution.

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3

Reliability and Safety Basics

3.1 Introduction

The history of the reliability field may be traced back to the early 1930s, when probability concepts were applied to problems associated with electric power generation. However, its real beginning is generally regarded as World War II, when German scientists applied basic reliability concepts to improve the performance of their V1 and V2 rockets [1–3]. Today, the reliability field has become a well-developed discipline and has branched out into many specialized areas, including mechanical reliability, power system reliability, software reliability, and human reliability and error [1, 4]. Additional information on the history of the reliability field is available in Dhillon [4].

The history of the safety field goes back to 1868, when a patent for a barrier safeguard was awarded in the United States [5]. In 1893, the U.S. Congress passed the Railway Safety Act. Today, the field of safety has branched out into specialized areas such as system safety, workplace safety, and patient safety. A detailed history of the safety field is given in Dhillon [6].

This chapter presents various reliability and safety basics considered useful to understand subsequent chapters of this book as well as for the transportation industry at large.

3.2 Bathtub Hazard Rate Curve

The bathtub hazard rate curve shown in Figure 3.1 is generally used to describe the failure rate of engineering items. As shown in the figure, the curve is divided into three regions: burn-in period, useful-life period, and wear-out period. During the burn-in period, the item hazard rate decreases with time t, and some of the reasons for the occurrence of failures during this period are poor manufacturing methods, poor quality control, substandard materials and workmanship, poor processes, inadequate debugging, and human error [4, 7]. Three other terms used for this decreasing hazard rate region are *break-in region*, *debugging region*, and *infant mortality region*.

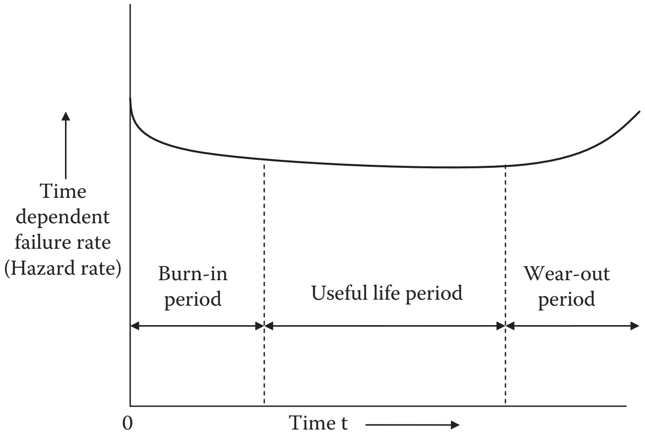

FIGURE 3.1
Bathtub hazard rate curve.

During the useful-life period, the hazard rate remains constant. Some of the reasons for the occurrence of failures in this region are low safety factors, abuse, higher random stress than expected, undetectable defects, natural failures, and human errors.

Finally, during the wear-out period, the hazard rate increases with time *t*. Some of the causes for the occurrence of failures in this region are poor maintenance; wear due to aging; wear due to friction, corrosion, and creep; incorrect overhaul practices; and short designed-in life of the item under consideration.

The following equation can be used to represent the bathtub hazard rate curve mathematically [8, 9]:

$$\begin{aligned}
&\lambda(t) = \theta\lambda m t^{m-1} + (1-\theta) n t^{n-1}\beta e^{\beta t^{n}} \\
&\text{for} \\
&m, n, \beta, \lambda \rangle 0 \\
&0 \leq \theta \leq 1 \\
&n = 1 \\
&m = 0.5 \\
&t \geq 0
\end{aligned} \tag{3.1}$$

where
t = time
$\lambda(t)$ = hazard rate or time-dependent failure rate
λ and β = scale parameters
m and n = shape parameters

3.3 General Reliability-Related Formulas

There are a number of general formulas used to perform various types of reliability analysis. Four of these formulas are presented below.

3.3.1 Failure (or Probability) Density Function

The failure (or probability) density function is defined as [4]

$$\mathrm{f(t)} = -\frac{dR(t)}{dt} \tag{3.2}$$

where
t = time
$f(t)$ = failure (or probability) density function
$R(t)$ = item reliability at time t

Example 3.1

Assume that the reliability of a transportation system is expressed by the following function:

$$R_s(t) = \mathrm{e}^{-\lambda_s t} \tag{3.3}$$

where
t = time
$R_{ts}(t)$ = transportation system reliability at time t
λ_{ts} = constant failure rate of the transportation system

Obtain an expression for the transportation system's failure density function by using Equation (3.2).

By inserting Equation (3.3) into Equation (3.2), we obtain

$$\begin{aligned} f(t) &= -\frac{de^{-\lambda_s t}}{dt} \\ &= \lambda_s e^{-\lambda_s t} \end{aligned} \tag{3.4}$$

Thus, Equation (3.4) is the expression for the transportation system's failure density function.

3.3.2 Hazard Rate Function

The hazard rate function is expressed by

$$\lambda(t) = \frac{f(t)}{R(t)} \tag{3.5}$$

where

$\lambda(t)$ = item hazard rate (i.e., time-dependent failure rate)

Substituting Equation (3.2) into Equation (3.5) yields

$$\lambda(t) = -\frac{1}{R(t)} \cdot \frac{dR(t)}{dt} \tag{3.6}$$

Example 3.2

Obtain an expression for the transportation system's hazard rate by using Equations (3.3) and (3.6) and comment on the end result.

By substituting Equation (3.3) into Equation (3.6), we get

$$\begin{aligned}\lambda(t) &= -\frac{1}{e^{-\lambda_s t}} \cdot \frac{de^{-\lambda_s t}}{dt} \\ &= \lambda_s\end{aligned} \tag{3.7}$$

Thus, the transportation system's hazard rate is given by Equation (3.7), and the right-hand side of this equation is not a function of time *t*. Needless to say, λ_s is generally referred to as the constant failure rate of an item (in this case, of the transportation system) because it does not depend on time *t*.

3.3.3 General Reliability Function

The general reliability function can be obtained by using Equation (3.6). Thus, we have

$$-\lambda(t)dt = \frac{1}{R(t)} . dR(t) \tag{3.8}$$

By integrating both sides of Equation (3.8), we obtain

$$\int_0^t \lambda(t)dt = \int_1^{R(t)} \frac{1}{R(t)} dR(t) \tag{3.9}$$

since, at $t = 0$, $R(t) = 1$.

Evaluating the right-hand side of Equation (3.9) and rearranging yields

$$\ln R(t) = -\int_0^t \lambda(t)dt \tag{3.10}$$

Thus, from Equation (3.10), we obtain

$$R(t) = e^{-\int_0^t \lambda(t)dt} \tag{3.11}$$

Equation (3.11) is the general expression for the reliability function. Thus, it can be used to obtain the reliability of an item when its times to failure follow any time-continuous probability distribution (e.g., exponential, Weibull, and Rayleigh).

Example 3.3

Assume that the times to failure of a transportation system are exponentially distributed and that the constant failure rate is 0.007 failures per hour. Calculate the transportation system's reliability for a 4-hour mission.

By substituting the given data values into Equation (3.11), we get

$$\begin{aligned} R(4) &= e^{-\int_0^4 (0.007)dt} \\ &= e^{-(0.007)(4)} \\ &= 0.9724 \end{aligned}$$

Thus, the transportation system's reliability is 0.9724. In other words, there is a 97.24% chance that the transportation system will not fail during the specified time period.

3.3.4 Mean Time to Failure

Mean time to failure can be obtained by using any of the following three formulas [10, 11]:

$$MTTF = \int_0^\infty R(t)dt \tag{3.12}$$

or

$$MTTF = E(t) = \int_0^\infty tf(t)dt \tag{3.13}$$

or

$$MTTF = \lim_{s \to 0} R(s) \tag{3.14}$$

where

MTTF = mean time to failure
s = Laplace transform variable
$R(s)$ = Laplace transform of the reliability function $R(t)$
$E(t)$ = expected value

Example 3.4

Prove by using Equation (3.3) that Equations (3.12) and (3.14) yield the same result for the transportation system mean time to failure. By substituting Equation (3.3) into Equation (3.12), we obtain

$$\begin{aligned} MTTF_s &= \int_0^{\infty} e^{-\lambda_s t}\,dt \\ &= \frac{1}{\lambda_s} \end{aligned} \tag{3.15}$$

where

MTTF_s = transportation system mean time to failure

By taking the Laplace transform of Equation (3.3), we get

$$\begin{aligned} R_s(s) &= \int_0^{\infty} e^{-st} e^{-\lambda_s t}\,dt \\ &= \frac{1}{s+\lambda_s} \end{aligned} \tag{3.16}$$

where

$R_s(s)$ = Laplace transform of the transportation system reliability function $R_s(t)$

Inserting Equation (3.16) into Equation (3.14) yields

$$\begin{aligned} MTTF_s &= \lim_{s \to 0} \frac{1}{s+\lambda_s} \\ &= \frac{1}{\lambda_s} \end{aligned} \tag{3.17}$$

Equations (3.17) and (3.15) are identical, proving that Equations (3.12) and (3.14) yield the same mean-time-to-failure result for the transportation system.

3.4 Reliability Networks

A system in the area of transportation can form various configurations in conducting reliability analysis. This section is concerned with the reliability evaluation of such commonly occurring configurations or networks.

3.4.1 Series Network

The series network is the simplest reliability network or configuration, and its block diagram is shown in Figure 3.2. The diagram denotes an *m*-unit

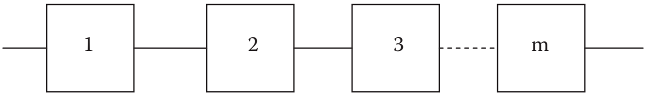

FIGURE 3.2
A m-unit series system.

system, and each block in the diagram represents a unit. For the successful operation of the series system, all m units must work normally. In other words, if any one of the m units fails, the series system fails.

The series system reliability, shown in Figure 3.2, is expressed by

$$R_s = P(E_1 E_2 E_3 .... E_m) \tag{3.18}$$

where

R_s = series system reliability

E_i = successful operation (i.e., success event) of unit i, for $i = 1,2,3,\ldots,m$

$P(E_1 E_2 E_3 \ldots E_m)$ = occurrence probability of events $E_1, E_2, E_3, \ldots, E_m$

For independently failing units, Equation (3.18) becomes

$$R_s = P(E_1)P(E_2)P(E_3)....P(E_m) \tag{3.19}$$

where

$P(E_i)$ = probability of occurrence of event E_i, for $i = 1,2,3,\ldots,m$

If we let $R_i = P(E_i)$, for $i = 1,2,3,\ldots,m$, Equation (3.19) becomes

$$\begin{aligned} R_s &= R_1 R_2 R_3 .... R_m \\ &= \prod_{i=1}^{m} R_i \end{aligned} \tag{3.20}$$

where

R_i = unit i reliability for $i = 1,2,3,\ldots,m$

For constant failure rate λ_i of unit i from Equation (3.11) (i.e., $\lambda_i(t) = \lambda_i$), we obtain

$$R_i(t) = e^{-\lambda_i t} \tag{3.21}$$

where

$R_i(t)$ = reliability of unit i at time t

By inserting Equation (3.21) into Equation (3.20), we get

$$R_s(t) = e^{-\sum_{i=1}^{m} \lambda_i t} \tag{3.22}$$

where

$R_s(t)$ = series system reliability at time t

Using Equation (3.22) in Equation (3.12) yields the following expression for the series system mean time to failure:

$$MTTF_s = \int_0^{\infty} e^{-\sum_{i=1}^{m} \lambda_i t} dt$$
$$= \frac{1}{\sum_{i=1}^{m} \lambda_i} \tag{3.23}$$

where

MTTF$_s$ = series system mean time to failure

By substituting Equation (3.22) into Equation (3.6), we get the following expression for the series system hazard rate:

$$\lambda_s(t) = -\frac{1}{e^{-\sum_{i=1}^{m} \lambda_i t}} \left[-\sum_{i=1}^{m} \lambda_i \right] e^{-\sum_{i=1}^{m} \lambda_i t}$$
$$= \sum_{i=1}^{m} \lambda_i \tag{3.24}$$

where

$\lambda_s(t)$ = series system hazard rate

Note that the right-hand side of Equation (3.24) is independent of time *t*. Thus, the left-hand side of this equation is simply λ_s, the failure rate of the series system. It means that whenever we add up failure rates of items or units, we automatically assume that these items or units form a series configuration or network, a worst-case design scenario with respect to reliability.

Example 3.5

Assume that a road transportation system has six identical and independent tires and that the constant failure rate of each tire is 0.0009 failures per hour. All six tires must operate normally for the transportation system to operate successfully. Calculate the following:

- The transportation system reliability for an 8-hour mission with respect to tires
- The transportation system mean time to failure with respect to tires
- The transportation system failure rate with respect to tires

By substituting the specified data values into Equation (3.22), we get

$$R_s(8) = e^{-(0.0009)(6)(8)}$$
$$= 0.9577$$

Inserting the specified data values into Equation (3.23) yields

$$MTTF_s = \frac{1}{6(0.0009)}$$

$$= 185.18 \text{ hours}$$

Using the given data values in Equation (3.24) yields

$$\lambda_s = 6(0.0009)$$

$$= 0.0054 \text{ failures/hour}$$

Thus, the road transportation system reliability, mean time to failure, and failure rate with respect to tires are 0.9577, 185.18 hours, and 0.0054 failures/hour, respectively.

3.4.2 Parallel Network

In this case, the system is composed of *m* simultaneously operating items or units, and at least one of these items or units must operate normally for the successful operation of the system. The *m*-unit parallel system block diagram is shown in Figure 3.3, and each block in the diagram denotes a unit.

The failure probability of the parallel system shown in Figure 3.3 is expressed by

$$F_p = P(\bar{E}_1 \bar{E}_2 \bar{E}_3 \ldots. \bar{E}_m) \tag{3.25}$$

where

F_p = failure probability of the parallel system

$\bar{E}_i$ = failure (i.e., failure event) of unit *i*, for *i* = 1,2,3,…,*m*

$P(\bar{E}_1 \bar{E}_2 \bar{E}_3 \ldots. \bar{E}_m)$ = probability of occurrence of events $\bar{E}_1, \bar{E}_2, \bar{E}_3, \ldots.,\text{and}\, \bar{E}_m$.

For independently failing parallel units, Equation (3.25) is written as

$$F_p = P(\bar{E}_1)P(\bar{E}_2)P(\bar{E}_3)\ldots.P(\bar{E}_m) \tag{3.26}$$

where

$P(\bar{E}_i)$ = occurrence probability of failure event $\bar{E}_i$, for *i* = 1,2,3,…,*m*.

If we let $F_i = P(\bar{E}_i)$ for *i* = 1,2,3,…,*m*, then Equation (3.26) becomes

$$F_p = F_1 F_2 F_3 \ldots. F_m \tag{3.27}$$

where

F_i = the unit *i* failure probability for *i* = 1,2,3,…,*m*.

Subtracting Equation (3.27) from unity we obtain

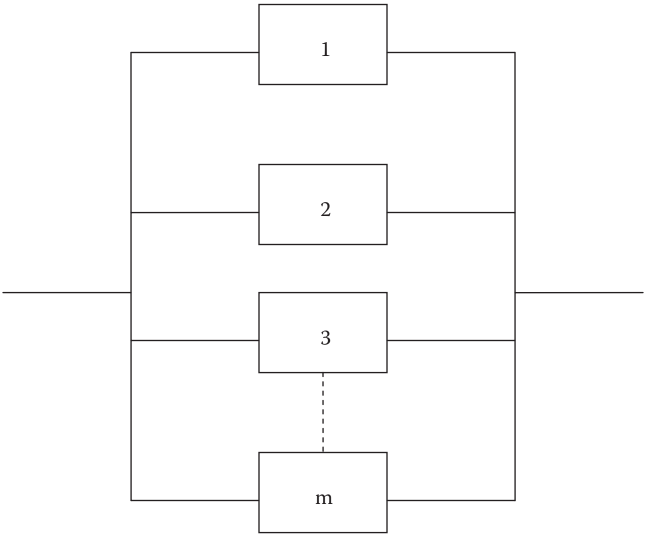

FIGURE 3.3
Block diagram of a parallel system with m units.

$$\begin{aligned} R_p &= 1 - F_p \\ &= 1 - F_1 F_2 F_3 \ldots . F_m \end{aligned} \tag{3.28}$$

where
R_p = parallel system reliability

For constant failure rate λ_i of unit *i*, subtracting Equation (3.21) from unity and then substituting it into Equation (3.28) yields

$$R_p(t) = 1 - (1 - e^{-\lambda_1 t})(1 - e^{-\lambda_2 t})(1 - e^{-\lambda_3 t}) \ldots . (1 - e^{-\lambda_m t}) \tag{3.29}$$

where
$R_p(t)$ = parallel system reliability at time *t*

For identical units, substituting Equations (3.29) into Equation (3.12) yields

$$\begin{aligned} MTTF_p &= \int_0^\infty \left[1 - (1 - e^{-\lambda t})^m\right] dt \\ &= \frac{1}{\lambda} \sum_{i=1}^{m} \frac{1}{i} \end{aligned} \tag{3.30}$$

where
$MTTF_p$ = parallel system mean time to failure
λ = unit constant failure rate

Example 3.6

Assume that a transportation system has three independent, identical, and active engines. At least one of the engines must operate normally for the transportation system to operate successfully. Calculate the transportation system's reliability with respect to engines if each engine's failure probability is 0.1

By substituting the given data values into Equation (3.28), we get

$$R_p = 1 - (.1)(0.1)(0.1)$$

$$= 0.999$$

Thus the transportation system's reliability with respect to engines is 0.999.

Example 3.7

Assume that a transportation system has two independent and identical units in parallel. The constant failure rate of a unit is 0.005 failures per hour. Calculate the transportation system mean time to failure.

By substituting the specified data values into Equation (3.30), we get

$$MTTF_p = \frac{1}{(0.005)}\left[1 + \frac{1}{2}\right]$$

$$= 300 \text{ hours}$$

Thus, the transportation system mean time to failure is 300 hours.

3.4.3 *k*-out-of-*m* Network

This is another form of redundancy in which at least k units out of a total of m active units must operate normally for the successful system operation. The block diagram of a k-out-of-m unit system/network is shown in Figure 3.4. Each block in the diagram represents a unit. The series and parallel networks are special cases of this network for $k = m$ and $k = 1$, respectively.

Using the binomial distribution, for independent and identical units, we write down the following expression for reliability of k-out-of-m unit network shown in Figure 3.4:

$$R_{k/m} = \sum_{i=k}^{m} \binom{m}{i} R^i (1 - R)^{m-i} \tag{3.31}$$

where

$$\binom{m}{i} = \frac{m!}{(m-i)!\,i!} \tag{3.32}$$

R = unit reliability

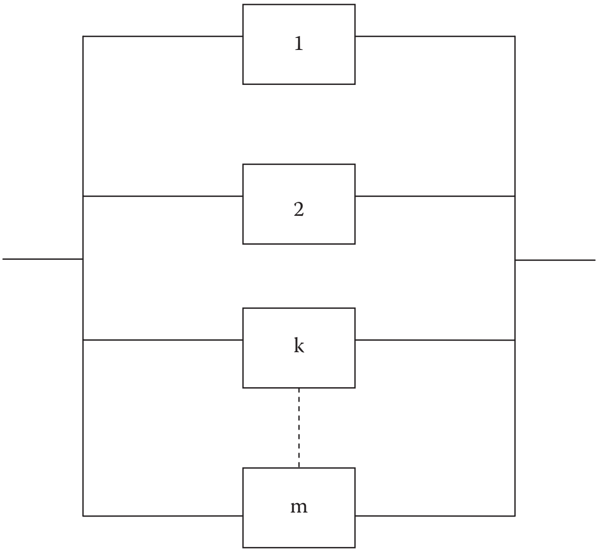

FIGURE 3.4
k-out-of-m unit network block diagram.

$R_{k/m}$ = k-out-of-m-network reliability

For constant failure rates of the identical units, using Equations (3.11) and (3.31), we get

$$R_{k/m}(t) = \sum_{i=k}^{m} \binom{m}{i} e^{-i\lambda t}(1 - e^{-\lambda t})^{m-i} \tag{3.33}$$

where

λ = unit constant failure rate

$R_{k/m}(t)$ = k-out-of-m network reliability at time t

By substituting Equation (3.33) into Equation (3.12), we obtain

$$MTTF_{k/m} = \int_0^{\infty} \left[\sum_{i=k}^{m} \binom{m}{i} e^{-i\lambda t}(1 - e^{-\lambda t})^{m-i} \right] dt$$

$$= \frac{1}{\lambda} \sum_{i=k}^{m} 1/i \tag{3.34}$$

where

$MTTF_{k/m}$ = k-out-of-m-network mean time to failure

Example 3.8

A transportation system has three independent and identical units in parallel. At least two units must operate normally for the successful operation of the transportation system. Calculate the transportation system mean time to failure if the unit constant failure rate is 0.0007 failures per hour. By substituting the specified data values into Equation (3.34), we get

$$MTTF_{2/3} = \frac{1}{(0.0007)} \sum_{i=2}^{3} 1/i$$

$$= 1190.48 \text{ hours}$$

Thus, the transportation system mean time to failure is 1190.48 hours.

3.4.4 Standby System

This is another reliability network or configuration in which only one unit operates and n units are kept in their standby mode. The total system contains (n + 1) units, and as soon as the operating unit fails, the switching mechanism detects the failure and turns on one of the standby units. The system fails when all the standby units fail. The block diagram of a standby system with one operating and n standby units is shown in Figure 3.5. Each block in the diagram represents a unit.

Using the diagram in Figure 3.5 for identical and independent units, time-dependent unit failure rate, and perfect switching mechanism and standby units, we write down the following expression for the standby system reliability [12]:

$$R_{ss}(t) = \sum_{i=0}^{n} \left[\left[\int_0^t \lambda(t)dt \right]^i e^{-\int_0^t \lambda(t)dt} \right] / i! \tag{3.35}$$

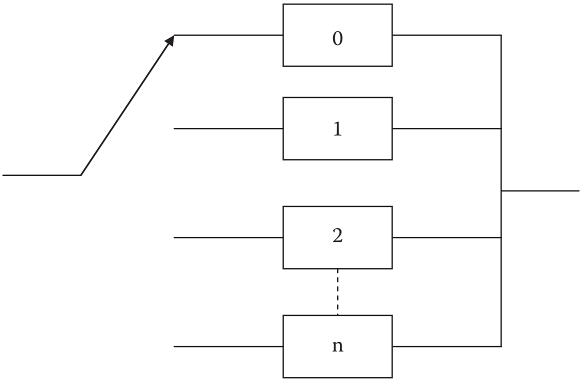

FIGURE 3.5
Block diagram of a standby system with one operating and n standby units.

where

$\lambda(t)$ = unit time-dependent failure rate or hazard rate

$R_{ss}(t)$ = standby system reliability at time t

For constant unit failure rate (i.e., $\lambda(t) = \lambda$), Equation (3.35) yields

$$R_{ss}(t) = \left[\sum_{i=0}^{n} (\lambda t)^i e^{-\lambda t}\right] / i! \tag{3.36}$$

where

λ = unit constant failure rate

By substituting Equation (3.36) into Equation (3.12), we obtain

$$\begin{aligned} MTTF_{ss} &= \int_0^\infty \left[\left[\sum_{i=0}^{n} (\lambda t)^i e^{-\lambda t}\right] / i!\right] dt \\ &= \frac{n+1}{\lambda} \end{aligned} \tag{3.37}$$

where

$MTTF_{ss}$ = standby system mean time to failure

Example 3.9

Assume that a standby system is composed of two identical and independent units (i.e., one operating, the other on standby). The unit constant failure rate is 0.005 failures per hour.

Calculate the standby system reliability for a 150-hour mission and mean time to failure, assuming that the switching mechanism is perfect and the standby unit remains as good as new in its standby mode.

By inserting the given data values into Equation (3.36), we obtain

$$\begin{aligned} R_{ss}(150) &= \sum_{i=0}^{1} \left[\left[(0.005)(150)\right]^i e^{-(0.005)(150)}\right] / i! \\ &= 0.8266 \end{aligned}$$

Similarly, by substituting the specified data values into Equation (3.37), we get

$$\begin{aligned} MTTF_{ss} &= \frac{2}{(0.005)} \\ &= 400 \text{ hours} \end{aligned}$$

Thus, the standby system reliability and mean time to failure are 0.8266 and 400 hours, respectively.

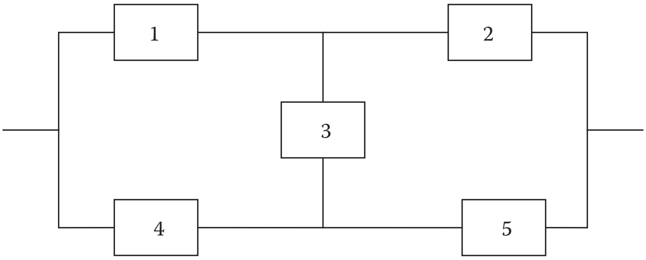

FIGURE 3.6
A five dissimilar unit bridge network.

3.4.5 Bridge Network

Sometimes units in transportation systems may form a bridge network, as shown in Figure 3.6. Each block in the figure represents a unit, and all units are labeled with numerals.

For independently failing units in the bridge network shown in Figure 3.6, reliability is given by [13]

$$\begin{aligned} R_{bn} &= 2R_1R_2R_3R_4R_5 + R_1R_3R_5 + R_2R_3R_4 + R_2R_5 + R_1R_4 \\ &-R_1R_2R_3R_4 - R_1R_2R_3R_5 - R_2R_3R_4R_5 - R_1R_2R_4R_5 - R_3R_4R_5R_1 \end{aligned} \tag{3.38}$$

where

R_{bn} = bridge network reliability

R_{i} = ith unit reliability for i = 1,2,3,4,5

For identical units, Equation (3.38) simplifies to

$$R_{bn} = 2R^5 - 5R^4 + 2R^3 + 2R^2 \tag{3.39}$$

where

R = unit reliability

For constant unit failure rate, using Equation (3.11) and Equation (3.39), we get

$$R_{bn}(t) = 2e^{-5\lambda t} - 5e^{-4\lambda t} + 2e^{-3\lambda t} + 2e^{-2\lambda t} \tag{3.40}$$

where

λ = unit constant failure rate

$R_{\mathrm{bn}}(t)$ = bridge network reliability at time t

Using Equation (3.40) in Equation (3.12) yields

$$MTTF_{bn} = \frac{49}{60\lambda} \tag{3.41}$$

where

$\mathrm{MTTF}_{\mathrm{bn}}$ = bridge network mean time to failure

Example 3.10

Assume that a transportation system has five independent and identical units forming a bridge network. The constant failure rate of each unit is 0.0007 failures per hour. Calculate the bridge network reliability for a 200-hour mission.

By substituting the given data values into Equation (3.41) we get

$$R_{bn}(200) = 2e^{-5(0.0007)(200)} - 5e^{-4(0.0007)(200)} + 2e^{-3(0.0007)(200)} + 2e^{-2(0.0007)(200)}$$

$$= 0.9627$$

Thus, the bridge network reliability is 0.9627.

3.5 Occupational Stressors and Reasons for Occurrence of Human Error

There are many occupational stressors that may compromise transportation system reliability and safety. These stressors may be classified under four categories, as shown in Figure 3.7 [6, 14]. The categories are workload-related stressors, occupational frustration-related stressors, occupational change-related stressors, and miscellaneous stressors.

The workload-related stressors are associated with work overload or work under load. In the case of work overload, the job requirements exceed the individual's ability to satisfy them effectively. Similarly, in the case of work

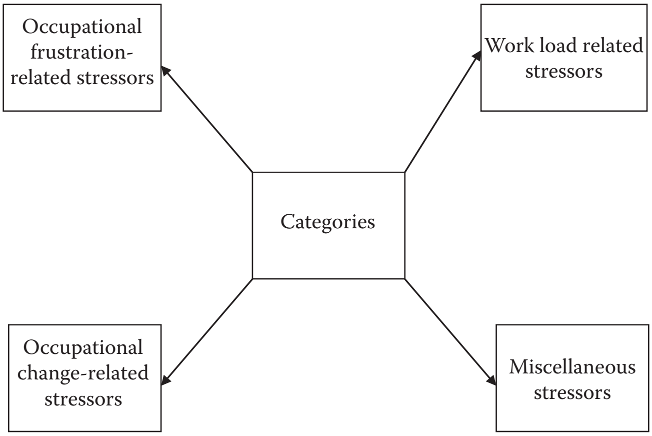

FIGURE 3.7
Occupational stressors' categories.

under load, the current duties being performed by the individual do not provide sufficient stimulation. Typical examples of work under load include the lack of opportunity to use acquired skills and expertise of the individual, the lack of any intellectual input, and task repetitiveness.

The occupational frustration-related stressors are associated with the problems concerning occupational frustration. Some examples of these problems are poor career development guidance, the ambiguity of one's role, and the lack of effective communication. The occupational change-related stressors are associated with factors that disrupt the functioning of physiological, cognitive, and behavioral patterns of the individual.

Finally, the miscellaneous stressors include all those stressors that are not included in the previous three categories. Typical examples of the miscellaneous stressors include too much noise, too little or too much lighting, and poor interpersonal relationships.

Past experiences indicate that there are many reasons for the occurrence of human errors. Some of the important ones are as follows [6, 15]:

- Poor work layout
- Poor equipment design
- Improper work tools
- Poorly written equipment operating and maintenance procedures
- Complex task
- Poor verbal communication
- Inadequate lighting in the work area
- High temperature and noise in the work area
- Crowded workspace
- Poor training
- Poor management
- Poor motivation

3.6 Human Error Consequences and Classifications

There is a wide range of consequences of human error. The range can vary from minor consequences to very severe consequences, e.g., from insignificant delays in, say, transportation system performance to a very high loss of lives. Furthermore, consequences can vary from one piece of equipment to another, from one task to another, or from one situation to another.

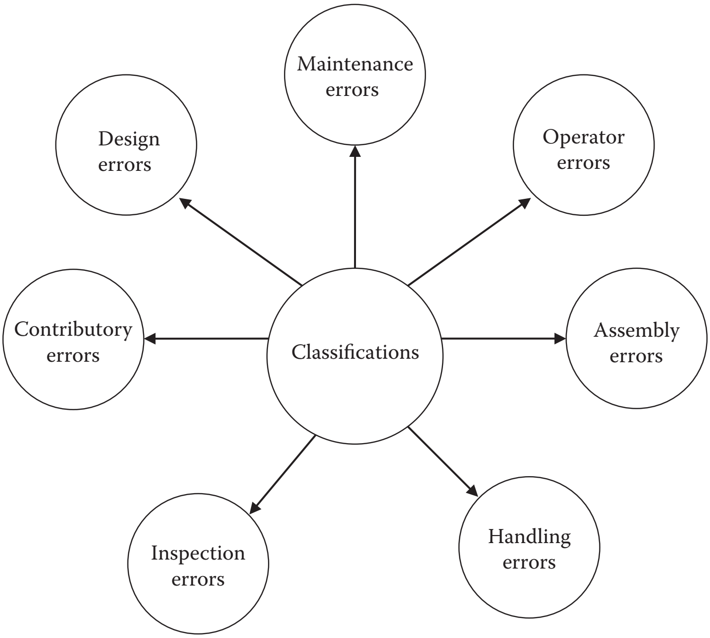

FIGURE 3.8
Common human error classifications.

In particular, in regard to equipment, the consequences of human error may be classified under the following three categories [6]:

- Equipment operation is stopped completely.
- Delay in equipment operation is insignificant.
- Equipment operation is delayed quite significantly but not stopped completely.

Human errors in the area of engineering may be grouped under a number of classifications. The seven commonly used classifications are shown in Figure 3.8 [6, 15–18]. Additional information on human error classifications shown in Figure 3.8 is available in the literature [4, 15–18].

3.7 Safety and Engineers

Nowadays, modern engineering products have become very complex and sophisticated. Their safety has become a challenging issue to engineers. Because of global competition and other factors, they are pressured to finish new designs rapidly and at lower costs. In turn, as per past experiences, this usually leads to more design shortcomings, errors, and causes of accidents.

Design-related shortcomings or deficiencies can contribute to accidents or cause accidents. Nonetheless, the design deficiency may result because a designer/design [19]:

- Failed to warn appropriately of a potential hazard
- Failed to eliminate or reduce the occurrence of human error
- Failed to prescribe an appropriate operational procedure in circumstances where a hazard might exist
- Failed to foresee an unexpected application of an item/system or all of its associated potential consequences
- Failed to provide an appropriate level of protection in a user's personal protective equipment
- Is wrong, confusing, or unfinished
- Relies on users of product to avoid an accident
- Incorporates rather weak warning mechanisms instead of providing a safe design for eradicating hazards
- Generates an unsafe characteristic of an item/system
- Places an unreasonable level of stress on product/system operators
- Does not properly determine or consider the error, failure, omission, or action consequences
- Violates usual tendencies/capabilities of potential product/system users
- Creates an arrangement of operating controls and other devices that increases reaction time in emergency circumstances or is quite conducive to human errors

3.8 Product Hazard Categories, Common Mechanical Injuries, and Common Causes of Work Injuries

There are many product hazards. They may be grouped into six categories as follows [20]:

- **Category 1: Electrical hazards.** These hazards have two principal elements: shock hazard and electrocution hazard. The major electrical hazard to product or system stems from electrical faults, often called *short circuits*.

- **Category 2: Environmental hazards.** These hazards may be grouped under two classifications: internal and external hazards. The internal hazards are concerned with the changes in the surrounding environment that result in an internally damaged product. A careful consideration to factors such as vibrations, ambient noise level, atmospheric contaminants, electromagnetic radiation, and extremes of temperatures during the design phase can help eliminate or minimize the internal hazards.

  The external hazards are the hazards posed by the product or system during its life span and include maintenance hazards, service-life operation hazards, and disposal hazards.
- **Category 3: Human factors hazards.** These hazards are concerned with poor design with respect to humans, i.e., to their physical strength, intelligence, weight, visual acuity, visual angle, computational ability, height, length of reach, education, etc.
- **Category 4: Energy hazards.** These hazards may be grouped under two classifications: potential energy and kinetic energy hazards. The potential energy hazards pertain to items that store energy. Some examples of these items are springs, counterbalancing weights, compressed-gas receivers, and electronic capacitors. During equipment servicing, such hazards are important because stored energy when released suddenly can cause serious injury.

  The kinetic energy hazards pertain to items that have energy because of their motion. Some examples of these items are fan blades, fly wheels, and loom shuttles. Any object that interferes with the motion of such items can experience extensive damage.
- **Category 5: Misuse-and-abuse hazards.** These hazards are concerned with the usage of a product by humans. Product misuse can cause serious injuries. Product abuse can also result in hazardous situations or injuries. Two examples of the causes for product abuse are lack of proper maintenance and poor operating practices.
- **Category 6: Kinematic hazards.** These hazards pertain to situations where items or parts come together while moving and lead to crushing, pinching, or cutting of any item or object caught between them.

In the industrial sector, including transportation, humans interact with various types of equipment to perform tasks such as stamping, drilling, cutting, and chipping. Past experience indicates that there are various types of injuries that can occur when performing tasks such as these. Some of the common ones are as follows [5]:

- **Crushing injuries.** These injuries occur when a body part is caught between two hard surfaces moving progressively together and crushing any item or object that comes between them.

- **Puncturing injuries.** These injuries occur in a situation when an object penetrates straight into the body of an individual and pulls straight out.
- **Shearing injuries.** These injuries are associated with shearing processes and include tragedies such as amputation of fingers/hands.
- **Cutting and tearing injuries.** These injuries occur when a body part of an individual comes in contact with a sharp edge.
- **Breaking injuries.** These injuries are usually associated with machines used to deform various types of engineering materials and can result in a simple fracture, complete fracture, transverse fracture, or oblique fracture.
- **Straining-and-spraining injuries.** These injuries are usually associated with the use of machines or other tasks. Example of such injuries include straining of muscles or spraining of ligaments.

Over the years, professionals involved in accident investigations have highlighted various causes of work injuries. Some of the common ones are as follows [6]:

- Overexertion
- Exposure to extreme temperatures
- Falls
- Exposure to radiation
- Motor vehicle accidents
- Impact accidents
- Bodily reaction (to chemicals)
- Rubbing or abrasions

According to a study performed by the National Safety Council of the United States, approximately 31% of all work-related injuries are caused by overexertion [5].

3.9 Accident Causation Theories

There are many theories of accident causation [5]. Two of these theories are described separately in the following subsections.

3.9.1 Domino Accident Causation Theory

This theory is encapsulated in 10 statements by H. W. Heinrich, known as the "Axioms of Industrial Safety" presented in Table 3.1 [21]. Furthermore, H. W.

TABLE 3.1

Industrial Safety Axioms

No.	Axioms
1	Most accidents are the result of unsafe acts of people.
2	Supervisors play an important role in industrial accident prevention.
3	The most helpful accident-prevention approaches are analogous to the quality and productivity methods.
4	The occurrence of injuries results from a completed sequence of a number of factors, the final or last one of which is the accident itself.
5	The severity of an injury is largely fortuitous, and the specific accident that caused it is normally preventable.
6	An unsafe act by a person or an unsafe condition does not always immediately result in an accident/injury.
7	Management should assume full safety responsibility with vigor because it is in the best position to achieve end results effectively.
8	The reasons why humans commit unsafe acts can be useful in selecting necessary corrective actions.
9	An accident can occur only when a person commits an unsafe act and/or there is a physical or mechanical-related hazard.
10	There are two types of costs of an accident: direct and indirect. Some examples of the direct costs are compensation, liability claims, medical costs, and hospital-related expenses.

Source: [21].

Heinrich believed that there are five specific factors in the sequence of events leading up to an accident [5, 6]:

- **Factor 1: Ancestry and social environment.** In this factor, it is assumed that negative character traits such as stubbornness, avariciousness, and recklessness that might lead humans to behave in an unsafe manner can be inherited through one's ancestry or acquired as a result of the social environment or surroundings.
- **Factor 2: Fault of person.** In this factor, it is assumed that negative character traits (whether acquired or inherited) such as violent temper, excitability, ignorance of safety-related practices, recklessness, and nervousness constitute proximate reasons to commit unsafe acts or for the existence of mechanical or physical hazards.
- **Factor 3: Unsafe act/mechanical or physical hazard.** In this factor, it is assumed that unsafe acts by humans (removing safeguards, standing under suspended loads, starting machinery/equipment without warning) and mechanical or physical hazards (inadequate light, unguarded point of operation, absence of guardrails, unguarded gears) are the direct causes for the occurrence of accidents.
- **Factor 4: Accident.** In this factor, it is assumed that events such as striking of humans by flying objects and falls of humans are the typical examples of accidents that result in injury.

- **Factor 5: Injury.** In this factor, it is assumed that the typical injuries directly resulting from the occurrence of accidents include lacerations and fractures.

3.9.2 Human Factors Accident Causation Theory

This theory is based on the assumption that accidents occur due to a chain of events directly or indirectly due to human error. It consists of the following three main factors that lead to the occurrence of human error [5, 22]:

- **Inappropriate activities.** Inappropriate activities carried out by an individual can be due to human error. For example, a person misjudged the degree of risk involved in a specified task and then carried out the task on that misjudgment.
- **Inappropriate response/incompatibility.** This is another major factor that can cause the occurrence of human errors. Three typical examples of inappropriate response would be when an individual (a) disregards the specified safety procedures, (b) detects a hazardous condition but takes no corrective action, and (c) removes a safeguard from a machine to increase output.
- **Overload.** This is concerned with an imbalance between a person's capacity at any time and the load that the individual is carrying in a given state. The capacity of a person is the product of factors such as stress, fatigue, degree of training, natural ability, state of mind, and physical condition. The load carried by a person is made up of tasks for which the individual has responsibility along with additional burdens resulting from the internal factors (i.e., worry, emotional stress, personal problems, etc.), environmental factors (i.e., noise, distractions, etc.), and situational factors (i.e., unclear instructions, level of risk, etc.).

Problems

1. Describe the bathtub hazard rate curve.
2. Write down general equations for the following:
    a. Hazard rate function
    b. Reliability function
    c. Failure density function
3. Write down three different formulas for mean time to failure.
4. A road transportation system has four identical tires and the failure rate of each tire is 0.005 failures per hour. All four tires must operate normally for the transportation system to operate successfully. Calculate the following:
    a. The transportation system reliability for a 10-hour mission with respect to tires
    b. The transportation system failure rate with respect to tires
    c. The transportation system mean time to failure with respect to tires

5. Assume that a transportation system has three independent and identical units in parallel. The failure rate of a unit is 0.004 failures per hour. Calculate the transportation system mean time to failure.
6. What are the special case networks of the *k*-out-of-*m* network?
7. Compare the standby system with the *k*-out-of-*m* network.
8. What are the main reasons for the occurrence of human errors?
9. Discuss the domino accident causation theory.
10. What are the common causes of work injuries?

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4

Methods for Performing Transportation System Reliability and Safety Analysis

4.1 Introduction

Over the years, a large amount of published literature in the areas of reliability and safety has appeared in the form of journal articles, conference proceedings articles, books, and technical reports [1–5]. Many of these publications report the development of various types of methods and techniques to perform reliability and safety analyses. Some of these methods and techniques can be used quite effectively to perform analysis in both reliability and safety areas. The others are more confined to a specific area (i.e., reliability or safety).

Three examples of these methods and techniques that can be used in both reliability and safety areas are failure modes and effect analysis (FMEA), fault-tree analysis (FTA), and the Markov method. FMEA was developed in the early 1950s to analyze the reliability of engineering systems. Similarly, the FTA approach was developed in the early 1960s to analyze the safety of rocket launch control systems. Today, both FMEA and FTA are being used across many diverse areas to analyze various types of problems.

The Markov method is named after a Russian mathematician, Andrei A. Markov (1856–1922), and is a highly mathematical approach that is often used to perform various types of reliability and safety analyses in engineering systems. This chapter presents a number of methods and techniques considered useful in analyzing the reliability and safety of transportation systems. All have been extracted from the published literature on reliability and safety.

4.2 Failure Modes and Effect Analysis (FMEA)

FMEA is a widely used design tool to analyze the reliability of engineering systems; it can be described as an approach for analyzing the effects of potential failure modes in the system [6]. The history of FMEA goes back to the early years of the 1950s with the development of flight control systems, when the U.S. Navy's Bureau of Aeronautics developed a requirement known as *failure analysis* to establish a mechanism for reliability control over the detail design effort [7]. Subsequently, the term *failure analysis* was changed to *failure modes and effect analysis* (FMEA). The seven main steps that are normally followed to perform FMEA are shown in Figure 4.1 [2, 6].

There are a number of factors that must be explored with care prior to the implementation of FMEA. Some of the factors are as follows [8, 9]:

- Examination of each conceivable failure mode by the involved professionals
- Measuring costs/benefits
- Obtaining engineer's approval and support
- Making decisions based on the risk priority number

Over the years, professionals involved with reliability analysis have established certain guidelines/facts concerning FMEA. Four of these guidelines/facts are shown in Figure 4.2 [8].

Some of the main advantages of performing FMEA are as follows [3, 8, 9]:

- A systematic approach to classify or categorize hardware failures
- A useful approach that begins from the detailed level and works upward
- A useful approach to compare designs and identify safety concerns
- A visibility tool for management that reduces product development time and cost
- A useful tool to improve communication between design interface personnel
- A useful tool to understand and improve customer satisfaction
- A useful approach to reduce engineering changes and to improve the efficiency of test planning
- A helpful tool to safeguard against repeating the same mistakes in the future

4.2.1 Failure Mode Effects and Criticality Analysis (FMECA)

FMECA is an extended version of FMEA. More specifically, when FMEA is extended to categorize or group each potential failure effect in regard to its level of severity (this includes documenting critical and catastrophic failures), the method is referred to as FMECA. The FMECA method was

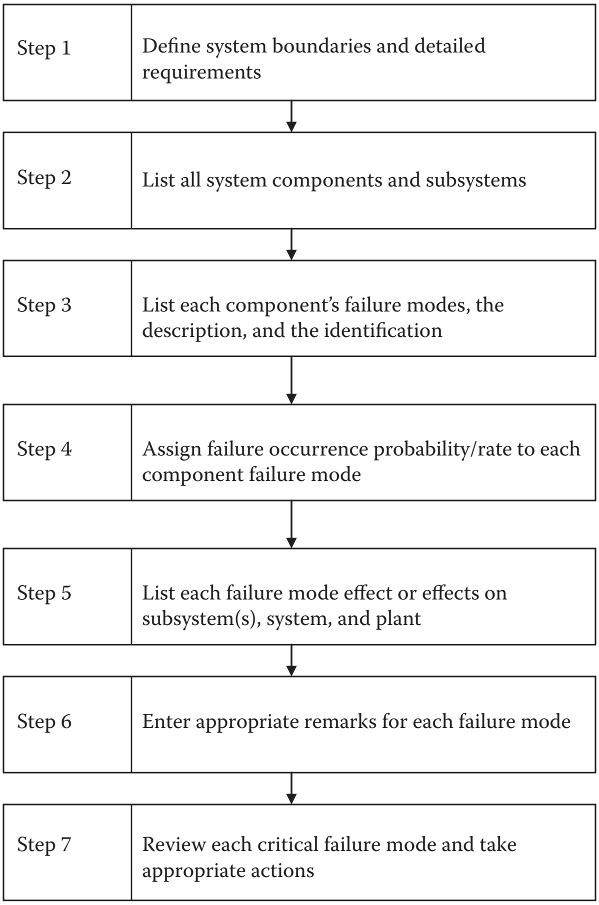

FIGURE 4.1
Steps for performing FMEA.

developed by the National Aeronautics and Astronautics Administration (NASA) to assure the specified reliability of space systems. In the 1970s, the U.S. Department of Defense developed a military standard entitled "Procedures for Performing a Failure Mode, Effects, and Criticality Analysis" [10].

Various types of information are needed to perform FMECA effectively. In particular, the design-related information needed for the FMECA includes system schematics, design descriptions, operating specifications and limitations, equipment/part drawings, interface specifications, functional block diagrams, field service data, reliability data, configuration management-related data, effects of environment on item under consideration, and relevant specifications (i.e., company, customer, etc.) [3].

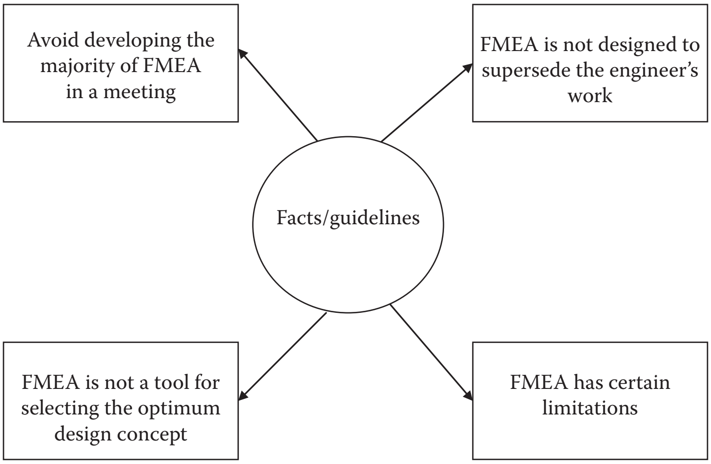

FIGURE 4.2
FMEA related facts/guidelines.

4.3 Fault-Tree Analysis (FTA)

This is a widely used method in the industrial sector to evaluate the reliability of engineering systems during their design and development phase, particularly in the area of nuclear power generation. A fault tree may simply be described as a logical representation of the relationship of basic events that lead to a specified undesirable event, known as the *top event*, and is depicted using a tree structure with AND, OR, etc., logic gates.

The fault-tree method was developed in the early 1960s at the Bell Telephone Laboratories to conduct analysis of the Minuteman Launch Control System [3]. Some of the main objectives of performing FTA are as follows [3, 5]:

- To identify critical areas and cost-effective improvements
- To understand the functional relationship of system failures
- To satisfy jurisdictional requirements
- To confirm the ability of the system to satisfy its imposed safety-related requirements
- To understand the degree of protection that the design concept provides against failures

There are many prerequisites associated with FTA, and some of the main ones are as follows [3]:

- Thorough understanding of design, operation, and maintenance aspects of system/item under consideration
- Clearly defined analysis scope and objectives
- Clear definition of what constitutes system/item failure: the undesirable event
- Clearly defined system/item physical bounds and system/item interfaces
- Clear identification of associated assumptions
- A comprehensive review of system/item operational experience

FTA starts by identifying an undesirable event, known as a top event, associated with a system/item under consideration. Fault events that can cause the occurrence of the top event are generated and connected by logic operators such as AND and OR. The AND gate provides a True output (i.e., fault) when all the inputs are true. Similarly, the OR gate provides a true output (i.e., fault) when one or more inputs are true.

The construction of a fault tree proceeds by generating fault events in a successive manner until the fault events need not be developed any further. These fault events are called basic or primary events. A fault tree is a logic structure that relates the top event to the basic or primary fault events. During the construction of a fault tree, one question that is successively asked is, "How could this fault event occur?"

Four basic symbols used to construct fault trees are shown in Figure 4.3.

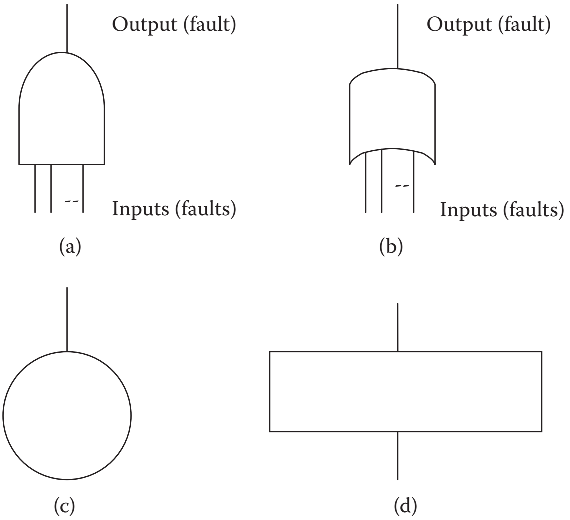

FIGURE 4.3
Basic fault tree symbols: (a) AND gate, (b) OR gate, (c) basic fault event, (d) resultant event.

The meanings of symbols/gates AND and OR have already been discussed. The remaining two symbols (i.e., circle and rectangle) are described as follows:

- **Circle.** It denotes a basic or primary fault event (e.g., failure of an elementary component or part), and the basic fault-event parameters are failure probability, failure rate, unavailability, and repair rate.
- **Rectangle.** It represents a resultant event that occurs from the combination of fault events through the input of a logic gate such as OR or AND.

Example 4.1

Assume that a windowless room contains four lightbulbs and one switch. Develop a fault tree for the undesired or top fault event, "dark room," if the switch can only fail to close.

In this case, there can only be no light in the room (i.e., dark room) if there is no incoming electricity, if the switch fails to close, or if all four of the lightbulbs burn out. A fault tree for the example, using symbols from Figure 4.3, is shown in Figure 4.4. The single capital letters in the diagram denote corresponding fault events (e.g., A: bulb No. 1 burnt out, I: no electricity, and E: power failure).

4.3.1 Probability Evaluation of Fault Trees

When the occurrence probabilities of basic or primary fault events are known, the top event probability of occurrence can be calculated. This can only be calculated by first calculating the occurrence probabilities of the output fault events of all the intermediate and lower logic gates (e.g., OR and AND gates).

Thus, the occurrence probability of the OR gate output fault event, A, is given by [3]

$$P(A) = 1 - \prod_{i=1}^{m} \{1 - P(A_i)\} \tag{4.1}$$

where

$P(\mathrm{A})$ = occurrence probability of the OR gate output fault event A
m = number of OR gate input fault events
$P(\mathrm{A_i})$ = probability of occurrence of the OR gate input fault event $\mathrm{A_i}$, for $i = 1,2,3,\ldots,m$

Similarly, the occurrence probability of the AND gate output fault event, B, is given by [3]

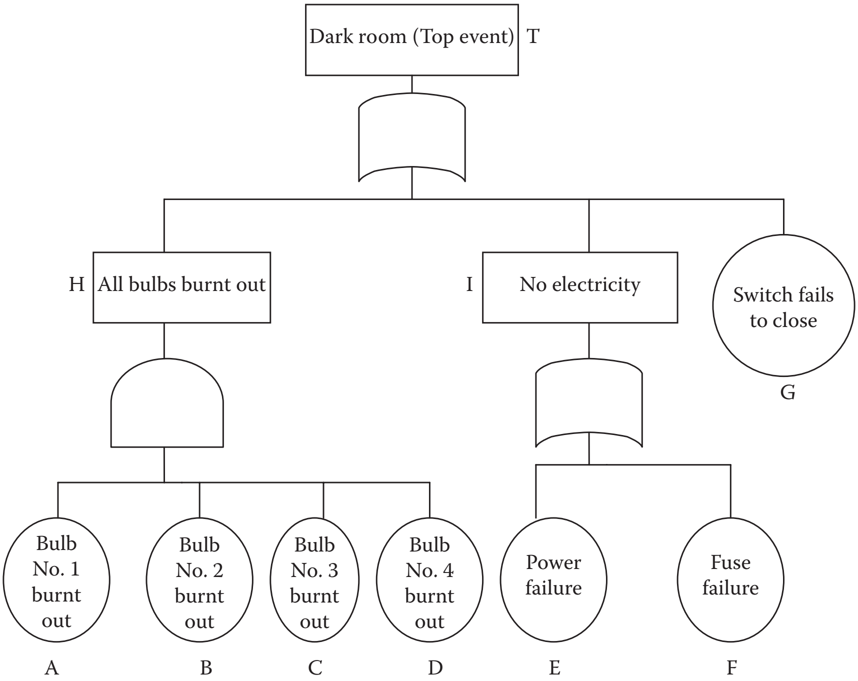

FIGURE 4.4
A fault tree for the top event: dark room.

$$P(\mathrm{B}) = \prod_{i=1}^{k} P(\mathrm{B}_i) \tag{4.2}$$

where

$P(\mathrm{B})$ = occurrence probability of the AND gate output fault event B
k = number of AND gate input fault events
$P(\mathrm{B}_i)$ = probability of occurrence of the AND gate input fault event B_i, for $i = 1,2,3,\ldots,k$.

Example 4.2

Assume that the occurrence probabilities of events A, B, C, D, E, F, and G in Figure 4.4 are .07, .06, .05, .04, .03, .02, and .01, respectively. Calculate the probability of occurrence of the top event T (dark room) by using Equations (4.1) and (4.2).

By substituting the given occurrence probability values of the events A, B, C, and D into Equation (4.2), we get

$$\begin{aligned} P(\mathrm{H}) &= (.07)\,(.06)\,(.05)\,(.04) \\ &= .0000084 \end{aligned}$$

where

$P(\mathrm{H})$ = probability of occurrence of event H (i.e., all bulbs burnt out)

Similarly, by substituting the given occurrence probability values of the events E and F into Equation (4.1), we get

$$\begin{aligned} P(\mathrm{I}) &= 1 - [(1 - .03)(1 - .02)] \\ &= .0494 \end{aligned}$$

where

$P(\mathrm{I})$ =probability of occurrence of event I (i.e., no electricity)

By substituting the above two calculated values and the given data value into Equation (4.1), we get

$$\begin{aligned} P(\mathrm{T}) &= 1 - [(1 - .0000084)(1 - .0494)(1 - .01)] \\ &= .0589 \end{aligned}$$

where

$P(\mathrm{T})$ = probability of occurrence of event T (i.e., dark room)

Thus, the probability of occurrence of the top event T (dark room) is .0589.

4.3.2 Fault-Tree Analysis (FTA) Benefits and Drawbacks

There are many benefits and drawbacks of the FTA. Some of its benefits are as follows [3, 5]:

- Useful in handling complex systems more easily
- Useful in highlighting failures deductively
- Requires the analyst to understand thoroughly the system under consideration prior to starting the analysis
- Provides insight into the system behavior
- Allows concentration on one particular failure at a time
- Serves as a graphic aid for system management
- Useful in providing options for management and others to conduct either qualitative or quantitative reliability analysis

In contrast, some of the drawbacks of the FTA are as follows [3, 5]:

- A costly and time-consuming approach
- Considers parts or components in either a working state or a failed state (i.e., partial-failure states of the components are difficult to handle)
- End results are difficult to check

4.4 Markov Method

This is a widely used method to perform reliability analysis of engineering systems and is named after the Russian mathematician, Andrei A. Markov (1856–1922). The method is commonly used to model repairable systems with constant failure and repair rates. The following assumptions are associated with the method [11]:

- All occurrences are independent of each other.
- The transitional probability from one system state to another in the finite time interval Δt is given by $\theta \Delta t$, where θ is the transition rate (e.g., failure or repair rate) from one system state to another.
- The probability of more than one transition occurrence in the finite time interval Δt from one system state to another is negligible (e.g., $[\theta \Delta t][\theta \Delta t] \to 0$).

The application of the Markov method is demonstrated by solving the following example.

Example 4.3

Assume that a transportation system can either be in an operating or a failed state. Its constant failure and repair rates are λ_{ts} and μ_{ts}, respectively. The system state-space diagram is shown in Figure 4.5. The numerals in boxes denote the transportation system states. Develop expressions for the system time-dependent and steady-state availabilities and unavailabilities, reliability, and mean time to failure by using the Markov method.

Using the Markov method, we write down the following equations for states 0 and 1, shown respectively in Figure 4.5.

$$P_0(t+\Delta t) = P_0(t)(1-\lambda_{ts}\Delta t) + P_1(t)\mu_{ts}\Delta t \tag{4.3}$$

$$P_1(t+\Delta t) = P_1(t)(1-\mu_{ts}\Delta t) + P_0(t)\lambda_{ts}\Delta t \tag{4.4}$$

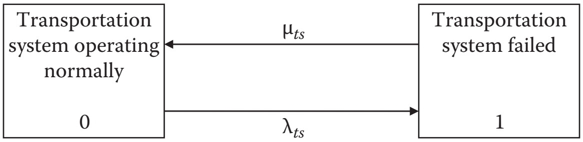

FIGURE 4.5
Transportation system state space diagram.

where

t = time
$\lambda_{st}\Delta t$ = probability of transportation system failure in finite time interval Δt
$\mu_{st}\Delta t$ = probability of transportation system repair in finite time interval Δt
$P_0(t + \Delta t)$ = probability of the transportation system being in operating state 0 at time $(t + \Delta t)$
$P_1(t + \Delta t)$ = probability of the transportation system being in failed state 1 at time $(t + \Delta t)$
$(1 - \lambda_{st}\Delta t)$ = probability of no failure in finite time interval Δt
$(1 - \mu_{st}\Delta t)$ = probability of no repair in finite time interval Δt
$P_i(t)$ = probability that the transportation system is in state i at time t, for $i = 0,1$.

From Equation (4.3), we get

$$P_0(t+\Delta t) = P_0(t) - P_0(t)\lambda_{ts}\Delta t + P_1(t)\mu_{ts}\Delta t \tag{4.5}$$

From Equation (4.5), we write

$$\lim_{\Delta t \to 0} \frac{P_0(t+\Delta t) - P_0(t)}{\Delta t} = -P_0(t)\lambda_{ts} + P_1(t)\mu_{ts} \tag{4.6}$$

Thus, from Equation (4.6), we obtain

$$\frac{dP_0(t)}{dt} + P_0(t)\lambda_{ts} = P_1(t)\mu_{ts} \tag{4.7}$$

Similarly, using Equation (4.4), we get

$$\frac{dP_1(t)}{dt} + P_1(t)\mu_{ts} = P_0(t)\lambda_{ts} \tag{4.8}$$

at time $t = 0$, $P_0(0) = 1$, and $P_1(0) = 0$.

Solving Equations (4.7) and (4.8), we obtain [3]

$$P_0(t) = \frac{\mu_{ts}}{(\lambda_{ts} + \mu_{ts})} + \frac{\lambda_{ts}}{(\lambda_{ts} + \mu_{ts})} e^{-(\lambda_{ts}+\mu_{ts})t} \tag{4.9}$$

$$P_1(t) = \frac{\lambda_{ts}}{(\lambda_{ts} + \mu_{ts})} - \frac{\lambda_{ts}}{(\lambda_{ts} + \mu_{ts})} e^{-(\lambda_{ts}+\mu_{ts})t} \tag{4.10}$$

Thus, the transportation system time-dependent availability and unavailability, respectively, are

$$A_{ts}(t) = P_0(t) = \frac{\mu_{ts}}{(\lambda_{ts} + \mu_{ts})} + \frac{\lambda_{ts}}{(\lambda_{ts} + \mu_{ts})} e^{-(\lambda_{ts}+\mu_{ts})t} \tag{4.11}$$

and

$$UA_{ts}(t) = P_1(t) = \frac{\lambda_{ts}}{(\lambda_{ts} + \mu_{ts})} - \frac{\lambda_{ts}}{(\lambda_{ts} + \mu_{ts})} e^{-(\lambda_{ts} + \mu_{ts})t} \tag{4.12}$$

where

$A_{ts}(t)$ = transportation system time-dependent availability
$U_{ts}(t)$ = transportation system time-dependent unavailability

By letting time t go to infinity in Equations (4.11) and (4.12), we get [3]

$$A_{ts} = \lim_{t \to \infty} A_{ts}(t) = \frac{\mu_{ts}}{\lambda_{ts} + \mu_{ts}} \tag{4.13}$$

and

$$UA_{ts} = \lim_{t \to \infty} U_{ts}(t) = \frac{\lambda_{ts}}{\lambda_{ts} + \mu_{ts}} \tag{4.14}$$

where

A_{ts} = transportation system steady-state availability
UA_{ts} = transportation system steady-state unavailability

For $\mu_{ts} = 0$, from Equation (4.9) we get

$$R_{ts}(t) = P_0(t) = e^{-\lambda_{ts}t} \tag{4.15}$$

where

$R_{ts}(t)$ = transportation system reliability at time t

By integrating Equation (4.15) over the time interval [0, ∞], we get the following expression for the transportation system mean time to failure [3]:

$$\begin{aligned} \text{MTTF}_{ts} &= \int_0^\infty e^{-\lambda_{ts}t}\,dt \\ &= \frac{1}{\lambda_{ts}} \end{aligned} \tag{4.16}$$

where

MTTF_{ts} = transportation system mean time to failure

Thus, the transportation system time-dependent and steady-state availabilities and unavailabilities, reliability, and mean time to failure are given by Equations (4.11), (4.13), (4.12), (4.14), (4.15), and (4.16), respectively.

Example 4.4

Assume that the constant failure and repair rates of a transportation system are 0.0004 failures/hour and 0.0008 repairs/hour, respectively. Calculate the transportation system steady-state availability and availability during a 10-hour mission.

By substituting the given data values into Equations (4.13) and (4.9), we get

$$A_{ts} = \frac{0.0008}{0.0004 + 0.0008} = 0.667$$

and

$$A_{ts}(10) = \frac{0.0008}{(0.0004 + 0.0008)} + \frac{(0.0004)}{(0.0004 + 0.0008)} e^{-(0.0004+0.0008)(10)}$$

$$= 0.9960$$

Thus, the transportation system steady-state availability and availability during a 10-hour mission are 0.6667 and 0.9960, respectively.

4.5 Hazards and Operability Analysis (HAZOP)

HAZOP is a systematic approach to identify hazards and operating problems in a facility. It has proved to be an extremely useful tool to highlight unforeseen hazards designed into facilities due to various reasons, or introduced into existing facilities due to factors such as changes made to process-related conditions or operating procedures. Three basic objectives of HAZOP are shown in Figure 4.6 [5, 12].

A HAZOP study can be performed in five steps. These steps are as follows [12]:

- **Step 1: Establish study objectives and scope.** This step is concerned with developing study objectives and scope by considering all relevant factors.
- **Step 2: Form HAZOP team.** This step is concerned with forming a HAZOP team by ensuring that the team comprises individuals from the area of design and operation with the necessary experience to determine the effects of deviations from the intended application.
- **Step 3: Collect relevant information.** This step is concerned with obtaining the required drawings, documentation, and process description, including such items as layout drawings, equipment specifica-

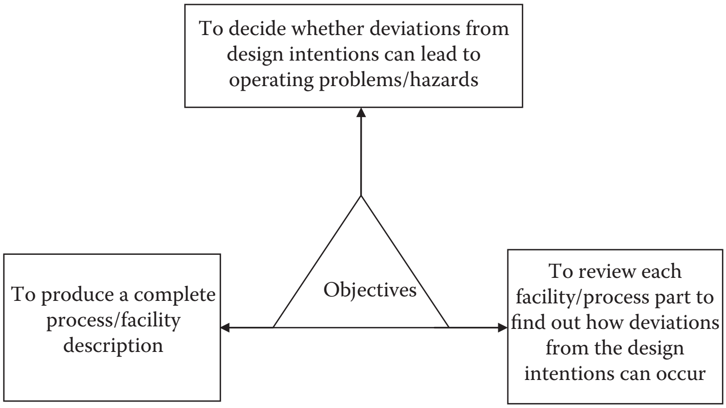

FIGURE 4.6
Basic HAZOP objectives.

tions, process flowsheets, process-control logic diagrams, operating and maintenance procedures, and emergency response procedures.

- **Step 4: Conduct analysis of all major pieces of equipment and supporting items.** This step is concerned with analyzing all major items of equipment as well as all supporting equipment, instrumentation, and piping by using Step 3 documents.
- **Step 5: Document the study.** This step is concerned with documenting the consequences of any deviation from the norm, as well as a summary of deviations from the norm and a summary of those deviations deemed credible and hazardous.

4.6 Interface Safety Analysis

Interface safety analysis (ISA) is concerned with determining the incompatibilities between assemblies and subsystems of an equipment/product that could result in accidents. ISA establishes that distinct parts/units can be integrated into a viable system and that normal operation of an individual unit or part will not impair the performance of or damage another part/unit or the entire system/equipment. Although ISA considers various relationships, they can be grouped under three classifications, as shown in Figure 4.7 [5, 13].

The physical relationships are concerned with the physical aspects of items/products. For example, two items/products might be very well designed and manufactured and operate quite well individually, but they

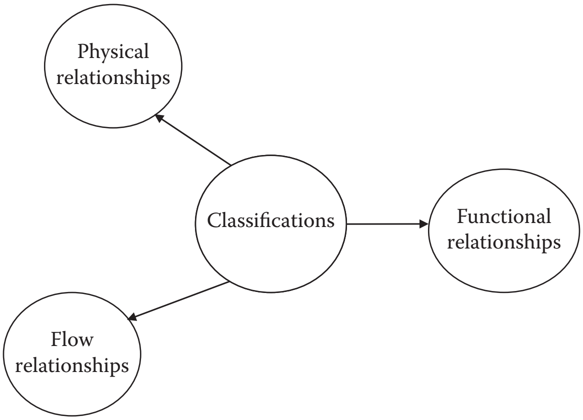

FIGURE 4.7
Classifications of relationships considered by ISA.

may have difficulties in fitting together effectively due to dimension-related differences, or there may be other incompatibilities that may lead to safety problems. Examples of the other problems are as follows:

- Impossible to tighten, mate, or join parts effectively
- Impossible or restricted access to or egress from equipment
- A quite small clearance between units; thus the units may be damaged during the removal process

The flow relationships are concerned with two or more units or items. For example, the flow between two items/units may involve air, steam, fuel, lubricating oil, water, or electrical energy. Furthermore, the flow could also be unconfined, such as heat radiation from one item/body to another. The frequent problems experienced with many products include the proper flow of energy and fluids from one unit to another unit through confined passages, consequently resulting in safety-related problems.

The causes of flow-related problems include faulty connections between units and total or partial interconnection failure. In the case of fluids, the factors that must be considered with care from the safety perspective include flammability, loss of pressure, toxicity, lubricity, contamination, and odor.

The functional relationships are concerned with multiple units or items. For example, in a circumstance where outputs of a unit constitute the inputs to the downstream unit(s), any error in outputs and inputs may lead to damage to the downstream unit(s), thereby creating a safety problem or hazard. Such outputs could be in conditions such as degraded outputs, unprogrammed outputs, zero outputs, excessive outputs, and erratic outputs.

4.7 Preliminary Hazard Analysis (PHA)

Preliminary Hazard Analysis (PHA) is a widely used method during the concept design phase. This is an unstructured approach that is used when there is a lack of definitive information such as functional flow diagrams and drawings. The method has proved to be an effective tool to take early measures to identify and eliminate possible hazards when all the necessary data are unavailable. Its findings are also considered useful to serve as a guide in potential detailed analysis.

PHA requires the formation of an ad hoc team of individuals with appropriate familiarity with items such as equipment, materials, substances, and/or the process in question. The team members review the occurrence of hazards in the area of their expertise and experience, and as a group they play the devil's advocate. Additional information on this method is available in Hammer and Price [4].

4.8 Job Safety Analysis

This method is concerned with uncovering and rectifying potential hazards that are intrinsic to or inherent in the workplace. Normally, the safety professional, workers, supervisors, and management take part in job safety analysis (JSA). JSA is performed in five steps [4].

- **Step 1:** Select a job for analysis.
- **Step 2:** Break down the job into a number of tasks or steps.
- **Step 3:** Identify all potential hazards and determine the necessary actions to control these hazards.
- **Step 4:** Apply the actions to control the hazards.
- **Step 5:** Evaluate the controls.

Note that the success of JSA depends on the rigor the JSA team exercises during analysis. Additional information on JSA is available in Hammer and Price [4].

4.9 Technique of Operations Review (TOR)

This method was developed in the early 1970s by D. A. Weaver of the American Society of Safety Engineers [5, 14]. It seeks to identify systemic causes for an adverse incident rather than assigning blame in regard to safety. The method allows workers and management to work jointly to analyze workplace incidents, accidents, and failures. Thus, TOR may simply be described as a hands-on analytical approach for identifying the root system causes of an operation failure [14].

The method uses a worksheet that contains simple terms that require yes/no decisions and is activated by an adverse incident occurring at a certain point in time and location involving certain individuals. Note that TOR is not a hypothetical process and demands a systematic evaluation of the circumstances surrounding the incident under consideration. Ultimately, the method identifies how the organization or company could have prevented the accident.

The method is composed of the following eight steps [5, 15]:

- **Step 1:** Form the TOR team with members from all concerned areas.
- **Step 2:** Hold a roundtable session for imparting common knowledge to all TOR team members.
- **Step 3:** Highlight one key systemic factor that played an instrumental role in causing the accident/incident. This factor must be based on the consensus of team members and serves as a starting point for further investigation.
- **Step 4:** Use the team consensus in responding to a sequence of yes/no options.
- **Step 5:** Evaluate the highlighted factors, ensuring that there is consensus among the team members in regard to the assessment of each and every factor.
- **Step 6:** Prioritize the contributory factors by starting with the most serious.
- **Step 7:** Develop appropriate corrective/preventive strategies in regard to each contributory factor.
- **Step 8:** Carry out the implementation of the strategies.

Finally, note that the main strength of the TOR is the involvement of line personnel in the analysis. In contrast, its main weakness is that it is an after-the-fact process.

Problems

1. Describe FMEA.
2. What is the difference between FMEA and FMECA?
3. What are the main objectives of performing fault-tree analysis?
4. What are the four basic symbols used to construct fault trees?
5. What are the advantages and disadvantages of FTA?
6. Assume that the occurrence probabilities of events A, B, C, D, E, F, and G in Figure 4.4 are .09, .08, .07, .06, .03, .01, and .05, respectively. Calculate the probability of occurrence of the top event T: dark room.
7. Prove Equations (4.9) and (4.10) by using Equations (4.7) and (4.8).
8. Describe hazards and operability analysis.
9. Discuss the following two methods:
    a. Technique of operations review
    b. Job safety analysis
10. Compare hazards and operability analysis (HAZOP) with preliminary hazard analysis (PHA).

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5

Transportation System Failures

5.1 Introduction

Each year, billions of dollars are spent worldwide to develop, manufacture, and operate transportation systems such as aircraft, motor vehicles, trains, and ships. These systems carry billions of tons of goods and billions of passengers annually from one point to another throughout the world. For example, as per the International Air Transportation Association (IATA), the world's airlines alone carry over 1.6 billion passengers for business and leisure travel each year, and over 40% of world trade of goods is carried by air [1].

Needless to say, transportation system failures have become an important issue, because they can, directly or indirectly, impact the global economy and the environment as well as transportation reliability and safety. In regard to safety, road transportation system failures alone, directly or indirectly, cause a vast number of fatalities and injuries worldwide each year [2, 3].

This chapter presents various important aspects of aircraft, motor vehicle, rail, and ship failures.

5.2 Mechanical Failure–Related Aviation Accidents

Over the years, there have been many aviation accidents due to mechanical failures and mechanical-related pilot errors (a mechanical-related pilot error is the one in which pilot error was the actual cause but brought about by some kind of mechanical failure). A worldwide study of 1,300 fatal accidents involving commercial aircraft (i.e., excluding aircraft with 10 or fewer people on board and helicopters), during the period 1950–2008, revealed 134 accidents due to mechanical failure and 25 accidents due to mechanical-related pilot error [4]. It is to be noted that these two types of accidents are out of those accidents whose cause was identifiable. The decade breakdowns of these two types of accidents are presented in Table 5.1 [4].

TABLE 5.1

Decade Breakdowns of World Fatal Commercial Aircraft Accidents due to Mechanical Failure and Mechanical-Related Pilot Error, 1950–2008

Accident Cause	Time Period (No. of Accidents)					
	1950–1959	1960–1969	1970–1979	1980–1989	1990–1999	2000–2008
Mechanical failure	21	20	23	21	21	28
Mechanical-related pilot error	7	5	4	2	4	3

Source: [4].

Some of the aviation accidents occurring due to mechanical failure are briefly described below.

- **US Air Flight 427 Accident.** This accident occurred on September 8, 1994, and is associated with the US Air Flight 427 (aircraft type: Boeing 737-387), a scheduled flight from Chicago's O'Hare Airport to West Palm Beach, Florida, via Pittsburgh, Pennsylvania [5]. The flight crashed due to rudder device malfunction and caused 132 fatalities.
- **Turkish Airlines Flight 981 Accident.** This accident occurred on March 3, 1974, and is associated with the Turkish Airlines Flight 981 (aircraft type: McDonnell Douglas DC-10-10), a scheduled flight from Istanbul, Turkey, to Heathrow Airport, London, U.K., via Paris, France [6]. The flight crashed due to cargo hatch failure and control cable failures and caused 346 fatalities.
- **United Airlines Flight 585 Accident.** This accident occurred on March 3, 1991, and is associated with the United Airlines Flight 585 (aircraft type: Boeing 737-291), a scheduled flight from Stapleton International Airport, Denver, Colorado, to Colorado Springs, Colorado [7]. The flight crashed due to rudder device malfunction and caused 25 fatalities.
- **Los Angeles Airways Flight 841 Accident.** This accident occurred on May 22, 1968, and is associated with the Los Angeles Airways Flight 841 (aircraft type: Sikorsky S-61L helicopter), a scheduled flight from Disneyland Heliport, Anaheim, California, to Los Angeles International Airport [8]. The flight crashed due to a mechanical failure in the blade rotor system and caused 23 fatalities.
- **British Overseas Airways Corporation (BOAC) Flight 781 Accident.** This accident occurred on January 10, 1954, and is associated with the BOAC Flight 781 (aircraft type: de Havilland DH-106 Comet 1), a scheduled flight from Kallang Airport, Singapore, to Heathrow

airport, London, U.K., via Rome, Italy [9]. The flight crashed into the Mediterranean Sea due to failure of the cabin pressure and caused 35 fatalities. The failure occurred because of metal fatigue caused by the repeated pressurization and depressurization of the aircraft cabin.

- **United Airlines Flight 859 Accident.** This accident occurred on July 11, 1961, and is associated with the United Airlines Flight 859 (aircraft type: Douglas DC-8-20), a scheduled flight from Omaha, Nebraska, to Stapleton International Airport, Denver, Colorado [10]. The flight crashed during landing at the Stapleton International Airport because the aircraft suffered a hydraulic failure while en route and caused 18 fatalities and 84 injuries.
- **1986 British International Helicopters Chinook Accident.** This accident occurred on November 6, 1986, and is associated with a Boeing 234LR Chinook helicopter operated by British International Helicopters [11]. The helicopter on approach to land at Sumburgh Airport, Shetland Islands, U.K., crashed into the sea and sank because of the failure of a modified level ring gear in the forward transmission. The accident resulted in 45 fatalities and 2 injuries.
- **Pan Am Flight 6 Accident.** This accident occurred on October 16, 1956, and is associated with the Pan American World Airways (Pan Am) Flight 6 (aircraft type: Boeing 377 Stratocruiser), a scheduled flight from Honolulu, Hawaii, to San Francisco, California [12]. The flight was forced to ditch in the Pacific Ocean because of the failure of two of its four engines. Fortunately, all people on board survived.

5.3 Vehicle Failure Classifications and Defects in Vehicle Parts

Failures of a vehicle carrying passengers can be categorized under four classifications [13]:

- **Classification I.** In this case, the vehicle is required to reduce speed but is allowed to continue to nearest station, where all of its passengers must egress, and then it is dispatched for maintenance.
- **Classification II.** In this case, the vehicle stops and it cannot be pushed/towed by adjacent vehicle, and it must wait for rescue vehicle.
- **Classification III.** In this case, the vehicle is allowed to continue to the closest station, where all its passengers must egress, and then it is dispatched for maintenance.

- **Classification IV.** In this case, the vehicle stops or is required to stop and is towed or pushed by adjacent vehicle to the closest station. At this point, people in both the affected vehicles egress, and the failed vehicle is towed or pushed for maintenance.

A motor vehicle is made up of many parts and subsystems such as brakes, engine, transmission, steering, clutch, and rim [14]. The failure of parts and subsystems such as these can result in motor vehicle failure. Defects in selective automobile parts are discussed below [14, 15].

- **Steering system defects.** These defects can lead to severe motor vehicle accidents. Some of the causes for the occurrence of the steering system defects are faulty design, poor maintenance, faulty manufacturing, inadequate inspection, and faulty changes made to the steering system.
- **Rim defects.** These defects are as important as defects in any other important part of a motor vehicle, because they can result in serious accidents. As per Limpert [14], one in approximately 1300–2200 truck tire failures results in an accident, and the findings of the U.S. Bureau of Motor Carrier Safety indicate that about 7%–13% of all tractors and trailers had at least one defective tire. The causes of the rim defects include poor design, faulty manufacturing operations, and abusive operation.
- **Brake defects.** In ordinary driving environments, the failure of parts in the motor vehicle braking system is likely to occur only when the parts become defective, degraded, or severely worn. Brake defects may be grouped under the following four categories:

  Disk brake system defects

  Drum brake system defects

  Air brake system defects

  Common disk and drum brake systems defects

The disk brake system defects include excessive wear of the pad, low or no brake force, and excessive brake pedal travel. Some of the defects belonging to the drum brake system defects category are brake jams, brake imbalance, low braking performance and hard pedal, noise generation during braking, brake pedal touching floor, and increasing heat in the brakes while driving the vehicle.

The air brake system defects include no or low brake force, slow brake response or release, and slow pressure build-up in the reservoir. Finally, some of the defects belonging to the common disk and drum brake systems defects category are brake pedal vibrations, soft pedal, brake fade, and excessive pedal force.

5.4 Rail Defects and Weld Failures

Although the wear resistance of rails is basically controlled by hardness, it is also dependent on the stresses that the rails are subjected to. These stresses control the development of defects in rails that can eventually lead to failure, and include bending stresses, residual stresses, thermal stresses, and contact stresses [16, 17].

The bending stresses act either vertically or laterally, and the vertical ones are mainly compressive in the rail head and tensile in the rail base. The residual stresses originate from manufacturing processes, whereas the thermal stresses originate from welding processes during the connection of rail sections to create a continuously welded rail. Finally, the contact stresses originate from the wheel load, traction, and steering and braking actions.

Defects in steel rails may be classified under the following three categories [16]:

- **Manufacturing defects.** These defects originate from the rail manufacturing process.
- **Inappropriate handling, installation, and use-related defects.** These defects originate from out-of-specifications installation of rails, wheel burns, and unexpected scratches.
- **Decrease of the metal's resistance to fatigue-related defects.** These defects include the most common rail defects such as squats and head checks.

In order to reduce the occurrence of rail-defect-related failures, various methods are used to detect rail defects. These methods include visual inspection by the track maintenance staff, ultrasonic defect detection, eddy-current testing, ground-penetrating radar, impedance spectroscopy, and electromagnetic acoustic transducers [16, 17].

In railway systems, the construction of continuous welded rails (CWR) is indispensable in reducing noise and vibration, improving the quality of the ride, and reducing the cost of track maintenance. Over the years, many railway accidents have occurred due to rail weld failures. Thus, it is very important to have reliable welds in order to eliminate the occurrence of weld failures in service as well as to extend the CWR service life.

Past experiences indicate that most rail weld failures are started from weld discontinuities, and fusion welding tends to easily cause such weld discontinuities [18]. Thus, fusion-welding techniques such as enclosed-arc welding (EA) and aluminothermic welding (TW) are less reliable than pressure-welding techniques such as flash welding (FW) and gas-pressure welding (GP) [18, 19]. In order to eliminate the occurrence of rail weld failures, it is very important to carry out reliable welding by using appropriate welding processes, welding conditions, well-trained welding technicians, and adequate inspection methods.

5.5 Mechanical Failure–Related Delays in Commuter Rail Service

Commuter rails are used in many North American cities. Many times, mechanical failure is the main cause for delays in commuter rail service. In fact, according to Nelson and O'Neil [20], approximately one-tenth of all commuter rail service delay minutes relate to mechanical causes such as the following:

- Wheel defects
- Traction motor defects
- Control system problems
- Electrical distribution problems
- Prime-mover failures
- Hotel and head-end power failures
- Coach problems

Nelson and O'Neil's study [20] presented the following distribution of percentages of delays due to commuter rail onboard equipment failures:

- **20%:** Delays caused by prime-mover (i.e., main engine) problems
- **13%:** Delays caused by braking system problems
- **7%:** Delays caused by power systems (hotel power) for passenger lighting and for problems related to heating, ventilation, and air conditioning
- **7%:** Delays caused by problems related to coach components such as doors, windows, toilets, and wipers in control cabs
- **5%:** Delays caused by wheel- and axle-related problems
- **2%:** Delays caused by traction-motor-related problems
- **2%:** Delays caused by control-system-related problems
- **2%:** Delays caused by problems related to electrical connections
- **42%:** Delays caused by unspecified problems

5.6 Rail and Road Tanker Failure Modes and Failure Consequences

Rail and road tankers are used to carry liquefied gases and other hazardous liquids from one point to another point. Over the years, the failure of such tankers has resulted in serious consequences. The main locations of failures are shells, pumps, valves, inspection covers, connections to a container, and branches, including instrument connections.

Rail and road tanker failure modes may be categorized under three main classifications, as shown in Figure 5.1 [21].

The main causes for failures due to excess internal pressure are abnormal meteorological conditions, flame impingement, tanker contents having higher vapor pressure than designed for, hydraulic rupture consequent upon overfilling, and internal chemical reaction such as decomposition or polymerization.

The main causes for mechanical failures other than overpressure include general wear and tear, collision with another vehicle, modifications in violation of original specifications, collision with a fixed object such as a bridge, collapse of a structure onto it, and damage by an external explosion.

Finally, the main causes for metallurgical failures include fatigue, erosion, corrosion (internal or external), vessel designed/constructed to an inadequate specification, use of incorrect or inadequate materials of construction, failure to satisfy specified construction codes, embrittlement by chemical action, and vessel used for purpose not covered by specification.

There are various consequences of rail and road tanker failures involving loss of containment. The nature of these consequences is influenced by the five principal factors shown in Figure 5.2 [21]. These are the nature of the surroundings, the physical state of the contents, the location and size of any

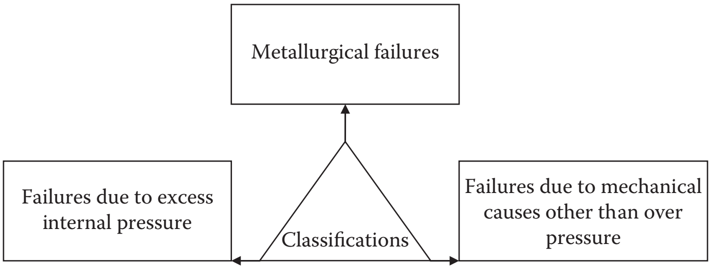

FIGURE 5.1
Rail and road tanker failure modes main classifications.

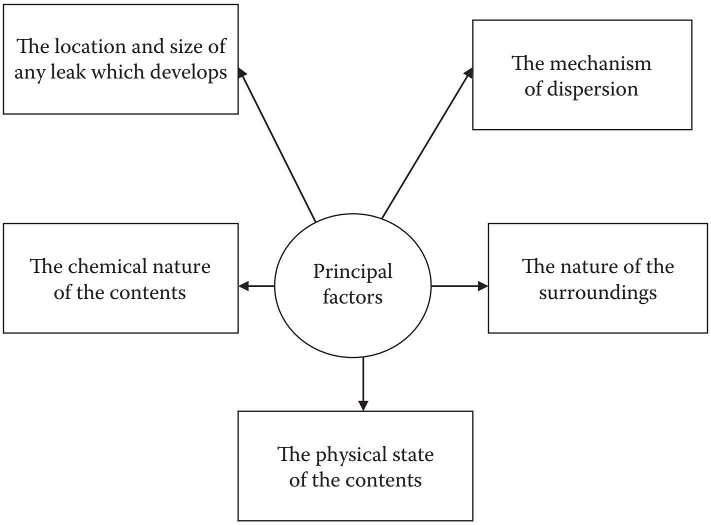

FIGURE 5.2
Principal factors influencing the nature of rail and road tanker loss of containment consequences.

leak that develops, the mechanism of dispersion, and the chemical nature of the contents. Additional information on these five factors is available in Marshall [21].

5.7 Ship Failures and Their Causes

The shipping industry is made up of many types of ships such as tankers, carriers, bulk cargo ships, and container ships. These ships contain various types of systems, equipment, and components that can occasionally fail. Examples of these system, equipment, and component failures are as follows:

- Pump failures
- Propulsion system failures
- Fuel tank failures
- Sensor failures
- Piping failures
- Weldment failures
- Boiler failures
- Heat-exchanger failures

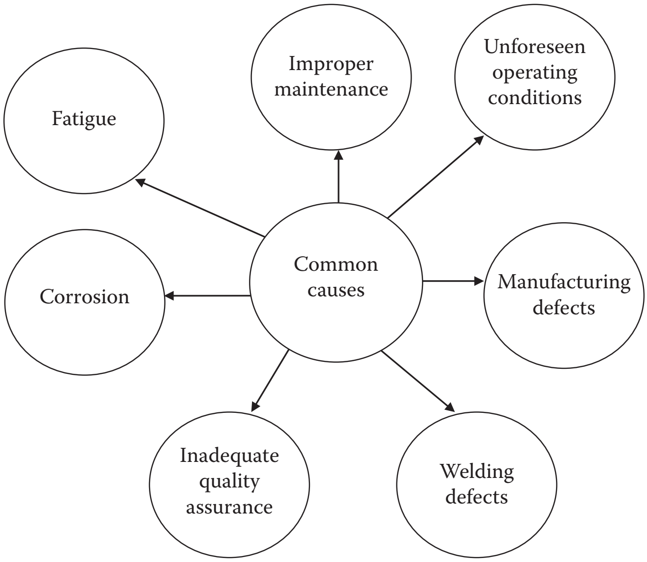

FIGURE 5.3
Common causes of ship failures.

The consequences of these failures can vary quite considerably. Nonetheless, there are many distinct causes for the occurrence of ship failures. Some of the common ones are shown in Figure 5.3.

5.8 Failures in Marine Environments and Microanalysis Techniques for Failure Investigation

Failures of systems, equipment, or components functioning in marine environments can have catastrophic effects. Nonetheless, before ships sink or lie dead in the water, a process usually occurs that causes the systems, equipment, or components to break down. The failure mechanism may be mechanical, electrical, chemical, or thermal [22].

A mechanical failure, for example, could occur as the result of an impact between a ship and another moving vessel or a stationery object. An electrical failure could occur as the result of internal partial discharges that degraded the insulation of a ship's propulsion motor. A chemical failure could occur as the result of corrosion of poorly protected parts/components on an offshore wind turbine. Finally, a thermal failure could be the result of heat generated by current flowing in an electrical conductor, causing insulation degradation.

Modern vessels contain many polymeric parts or components, such as pressure seals and electrical insulation, and some of these are critical to the vessel operation. There are a number of microanalysis techniques that are useful in failure investigations involving polymers. The commonly used microanalysis techniques are described in the following subsections [22].

5.8.1 Differential Scanning Calorimetry

Differential scanning calorimetry (DSC) measures heat flow to a polymer. This is important because, by monitoring the heat flow as a function of temperature, phase transitions such as crystalline melt temperatures and glass-transition temperatures can be characterized quite effectively. This, in turn, is quite useful to determine how a polymer will behave at operational temperatures.

The technique can also be used in forensic investigations to determine the maximum temperature that a polymer has been subjected to. This can be very useful in establishing whether an equipment/system/part has been subjected to thermal overloads during service. Finally, this method can also be used to determine the thermal stability of polymers by measuring the oxidation induction time/temperature.

5.8.2 Thermomechanical Analysis

Thermomechanical analysis involves measuring variations in a sample's volume or length as a function of temperature and/or time. The method is commonly used to determine thermal expansion coefficients as well as the glass-transition temperature of polymer or composite materials. A weighted probe is placed on the specimen surface, and the probe's vertical movement is monitored continuously while the sample is heated at a controlled rate.

5.8.3 Fourier Transform Infrared Spectroscopy

Fourier transform infrared spectroscopy is used to identify and characterize polymer materials and their additives. It is an extremely useful approach, particularly in identifying defects or inclusions in plastic films or molded parts. Additional information on the technique is available in Dean [22].

5.8.4 Thermogravimetric Analysis

Thermogravimetric analysis measures variations in the weight of a sample under consideration as a function of time or temperature. The technique is used to determine polymer degradation temperatures, absorbed moisture content, levels of residual solvent, and the degree of inorganic (i.e., noncombustible) filler in polymer or composite material compositions. The technique can also be useful in deformulation of complex polymer-based products.

5.9 Submarine Ship–Control System Performance Monitoring and Fault Localization Process and Benefits

Various types of ship-control systems are used in submarines. The ship-control system used in the Seawolf submarine represents the state of the art for such systems. This system incorporates various features, including a fault-tolerant computer, automatic modes of control for steering, and flat-panel operator displays [23]. High-speed data buses permit the ship control to interface effectively with the data distribution system, gyrocompass inertial sensors, and the combat system. Furthermore, hardware redundancy and performance-monitoring software permit the system to function after experiencing malfunctions of ship sensors, control electronics, and the actuation systems it controls.

After the occurrence of a failure, a totally separate computer is employed to carry out fault localization, which allows effective repair and restoration of full redundancy. The performance-monitoring software executes on the system's fault-tolerant computer and makes use of sensor voting and system mathematical models to detect failures. Real-time diagnostic tests are activated to identify suitable data paths and collect data required to carry out fault localization.

Performance monitoring activates or makes use of redundant parts or data paths to accommodate faults/failures. In the case of severe failures, performance monitoring makes the decision to transfer all ship-control-system-related functions to standby emergency backup systems. Additional information on the performance-monitoring and fault-localization processes is available in Hammett [23].

Some of the main advantages of the performance-monitoring/fault-localization functions are as follows [23]:

- Enhances the submarine mission effectiveness
- Reduces the degree of maintenance required
- Eliminates the need to take an immediate action in the event of a failure
- Simplifies the process of diagnosing which part or component within the ship control system has failed

- Helps to reduce the potential for damage to the ship's machinery
- Helps to prevent the occurrence of serious casualty conditions due to undetected machinery failures

Problems

1. Discuss the following mechanical failure–related aviation accidents:
   a. United Airlines Flight 859 accident
   b. US Air Flight 427 accident
   c. Turkish Airlines Flight 981 accident
2. Discuss vehicle failure classifications.
3. Describe the following defects associated with a vehicle:
   a. Steering system defects
   b. Brake defects
4. Discuss the classifications of defects in steel rails.
5. Discuss rail weld failures.
6. Discuss mechanical failure–related delays in commuter rail service.
7. What are the three main classifications of rail and road tanker failure modes? Describe each of these classifications in detail.
8. What are the principal factors that influence the nature and consequences of rail and road tanker loss of containment?
9. What are the common causes of ship failures?
10. Describe the following two items:
    a. Thermomechanical analysis
    b. Differential scanning calorimetry

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6

Transportation System Reliability Modeling

6.1 Introduction

Mathematical modeling is a commonly used approach to perform various types of analysis in the area of engineering. In this case, the components of an item are represented by idealized elements assumed to have all the representative characteristics of real-life components, and whose behavior can be described by equations. However, a mathematical model's degree of realism depends on the type of assumptions imposed upon it.

Over the years, a large number of mathematical models have been developed to perform various types of reliability-related analyses of engineering systems. Most of these models were developed using the Markov method. Although the effectiveness of such models can vary quite significantly from one situation to another, some of them are being used quite successfully to represent various types of real-life environments in the industrial sector [1–3]. Thus, some of these models can also be used to study transportation system reliability-related problems.

This chapter presents the mathematical models considered useful, directly or indirectly, in conducting various types of transportation system reliability-related analyses.

6.2 Model I

This mathematical model represents a three-state transit system in which a vehicle can be in any one of the three states: vehicle operating normally in the field, vehicle failed in the field, and failed vehicle in the workshop for repair. The failed vehicle is taken to the repair workshop from the field. The repaired vehicle is put back to its normal operating state.

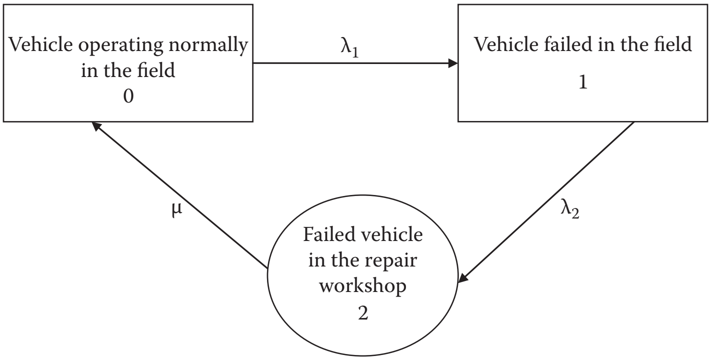

FIGURE 6.1
State space diagram for Model I.

The system state-space diagram is shown in Figure 6.1. The numerals in the boxes and circle denote system states. The following assumptions are associated with the model:

- Vehicle failure, towing, and repair rates are constant.
- Vehicle failures occur independently.
- A repaired vehicle is as good as new.

The following symbols are associated with the diagram:
i = ith state of the vehicle/transit system, where $i = 0$ (vehicle operating normally in the field), $i = 1$ (vehicle failed in the field), $i = 2$ (failed vehicle in the repair workshop)
λ_1 = vehicle constant failure rate
λ_2 = vehicle constant towing rate from state 1
μ = vehicle constant repair rate
$P_i(t)$ = probability that the vehicle/transit system is in state i at time t, for $i = 0,1,2$

Using the Markov method described in Chapter 4 and Figure 6.1, we write down the following equations [4]:

$$\frac{dP_0(t)}{dt} + \lambda_1 P_0(t) = \mu P_2(t) \tag{6.1}$$

$$\frac{dP_1(t)}{dt} + \lambda_2 P_1(t) = \lambda_1 P_0(t) \tag{6.2}$$

$$\frac{dP_2(t)}{dt} + \mu P_2(t) = \lambda_2 P_1(t) \tag{6.3}$$

At time $t = 0$, $P_0(0) = 1$, $P_1(0) = 0$, and $P_2(0) = 0$.

By solving Equations (6.1)–(6.3), we get the following steady-state probability equations [4]:

$$P_0 = \left[1 + \frac{\lambda_1}{\lambda_2} + \frac{\lambda_1}{\mu}\right]^{-1} \tag{6.4}$$

$$P_1 = \left(\frac{\lambda_1}{\lambda_2}\right) P_0 \tag{6.5}$$

$$P_2 = \left(\frac{\lambda_1}{\mu}\right) P_0 \tag{6.6}$$

where

P_0, P_1, and P_2 = steady-state probabilities of the vehicle/transit system being in states 0, 1, and 2, respectively

The vehicle/transit system steady-state availability is given by

$$AV_{vs} = P_0 \tag{6.7}$$

where

AV_{vs} = vehicle/transit system steady-state availability

By setting $\mu = 0$ in Equations (6.1)–(6.3) and then solving the resulting equations, we obtain

$$R_{vs}(t) = P_0(t) = e^{-\lambda_1 t} \tag{6.8}$$

where

$R_{vs}(t)$ = vehicle/transit system reliability at time t

The vehicle/transit system mean time to failure is given by [5]

$$\begin{aligned} MTTF_{vs} &= \int_0^\infty R_{vs}(t)\,dt \\ &= \int_0^\infty e^{-\lambda_1 t}\,dt \\ &= \frac{1}{\lambda_1} \end{aligned} \tag{6.9}$$

where

$MTTF_{vs}$ = vehicle/transit system mean time to failure

Example 6.1

Assume that a three-state transit system constant failure rate is 0.0005 failures/hour. Calculate the transit system reliability during a 10-hour mission and mean time to failure.

By substituting the given data values into Equation (6.8) we get

$$R_{vs}(10) = e^{-(0.0005)(10)}$$

$$= 0.9950$$

Using the specified data value in Equation (6.9) yields

$$MTTF_{vs} = \frac{1}{0.0005} = 2{,}000 \text{ hours}$$

Thus, the transit system reliability and mean time to failure are 0.9950 and 2,000 hours, respectively.

6.3 Model II

This mathematical model represents a four-state transit system in which a vehicle can be in any one of four states: vehicle operating normally in the field, vehicle degraded in the field, vehicle failed in the field, and failed or degraded vehicle in the repair workshop. More specifically, in this case, the operating vehicle performance may degrade due to the failure of some of its parts. If the degradation of the vehicle is serious, then it is driven to the repair workshop; otherwise it continues its operation in the field.

The vehicle may fail either from its normal operating state or from its degraded state. The failed vehicle is taken to the repair workshop. The fully repaired vehicle is put back into its normal operation. Also, the partially repaired vehicle is put back into its degraded operating state.

The system state-space diagram is shown in Figure 6.2. The numerals in boxes and circle denote system states.

The following assumptions are associated with the model:

- Vehicle failure, degradation, towing, and repair rates are constant.
- All vehicle failures occur independently.
- A repaired vehicle is as good as new.

The following symbols are associated with the model:

i = ith state of the vehicle/transit system, where $i = 0$ (vehicle operating normally in the field), $i = 1$ (vehicle degraded in the field), $i = 2$ (vehicle failed in the field), $i = 3$ (vehicle in the repair workshop)
λ_1 = vehicle constant degradation rate from state 0 to state 1
λ_2 = vehicle constant failure rate from state 1 to state 2
λ_3 = vehicle constant failure rate from state 0 to state 2
λ_4 = vehicle constant transition rate from state 1 to state 3
λ_5 = vehicle constant towing rate from state 2 to state 3 (includes the rate of taking the vehicle to the repair workshop by alternative means)

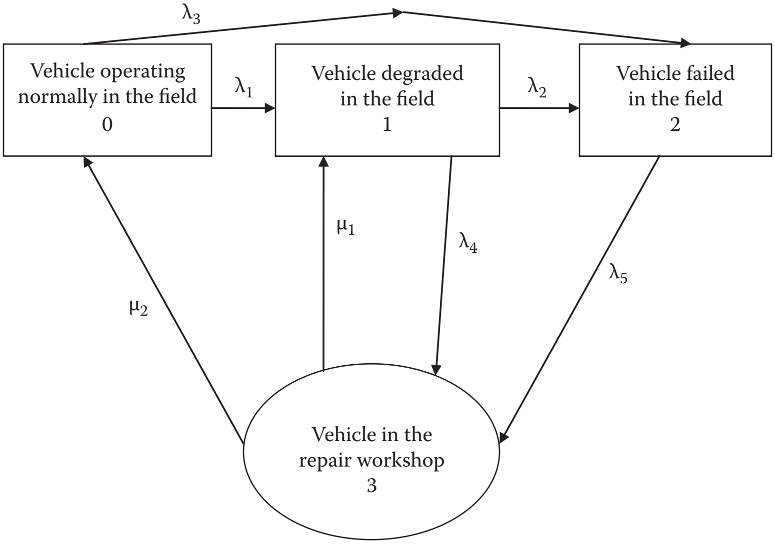

FIGURE 6.2
State space diagram for Model II.

μ_1 = vehicle constant repair rate from state 3 to state 1
μ_2 = vehicle constant repair rate from state 3 to state 0
$P_i(t)$ = probability that the vehicle/transit system is in state i at time t, for $i = 0,1,2,3$

By using the Markov method described in Chapter 4 and Figure 6.2, we write down the following equations [4]:

$$\frac{dP_0(t)}{dt} + (\lambda_1 + \lambda_2)P_0(t) = \mu_2 P_3(t) \tag{6.10}$$

$$\frac{dP_1(t)}{dt} + (\lambda_2 + \lambda_4)P_1(t) = \lambda_1 P_0(t) + \mu_1 P_3(t) \tag{6.11}$$

$$\frac{dP_2(t)}{dt} + \lambda_5 P_2(t) = \lambda_3 P_0(t) + \lambda_2 P_1(t) \tag{6.12}$$

$$\frac{dP_3(t)}{dt} + (\mu_1 + \mu_2)P_3(t) = \lambda_4 P_1(t) + \lambda_5 P_2(t) \tag{6.13}$$

At time $t = 0$, $P_0(0) = 1$, $P_1(0) = 0$, $P_2(0) = 0$, and $P_3(0) = 0$.

By solving Equations (6.10)–(6.13), we obtain the following steady-state probability equations [4]:

$$P_0 = \left[1 + B_2 + B_3 + B_4\right]^{-1} \tag{6.14}$$

where

$$B_2 = \frac{\lambda_1 + \lambda_3 B_1}{(\lambda_2 + \lambda_4)(1 - B_1)} \tag{6.15}$$

$$B_1 = \frac{\mu_1}{(\mu_1 + \mu_2)} \tag{6.16}$$

$$B_3 = (\lambda_3 + \lambda_2 B_2) / \lambda_5 \tag{6.17}$$

$$B_4 = \frac{(\lambda_4 B_2 + \lambda_5 B_3)}{(\mu_1 + \mu_2)} \tag{6.18}$$

$$P_1 = B_2 P_0 \tag{6.19}$$

$$P_2 = B_3 P_0 \tag{6.20}$$

$$P_3 = B_4 P_0 \tag{6.21}$$

where

P_0, P_1, P_2, and P_3 = steady-state probabilities of the vehicle/transit system being in states 0, 1, 2, and 3, respectively.

The vehicle/transit system steady-state availability is given by

$$AV_{vs} = P_0 + P_1 \tag{6.22}$$

where

AV_{vs} = vehicle/transit system steady-state availability

By setting $\mu_1 = \mu_2 = 0$ in Equations (6.10)–(6.13) and then solving the resulting equations, we get

$$R_{vs}(t) = P_0(t) + P_1(t)$$

$$= (1 + A)e^{-(\lambda_1+\lambda_3)t} - Ae^{-(\lambda_2+\lambda_4)t} \tag{6.23}$$

where

$$A = \frac{\lambda_1}{(\lambda_2 + \lambda_4 - \lambda_1 - \lambda_3)}$$

$R_{vs}(t)$ = vehicle/transit system reliability at time t

The vehicle/transit system mean time to failure is given by [5]

$$MTTF_{vs} = \int_0^\infty R_{vs}(t)dt$$

$$= \frac{(\lambda_1 + \lambda_2 + \lambda_4)}{(\lambda_1 + \lambda_3)(\lambda_2 + \lambda_4)} \tag{6.24}$$

where

$MTTF_{vs}$ = vehicle/transit system mean time to failure

Example 6.2

Assume that in Figure 6.2 we have the following data values:

$\lambda_1 = 0.004$ failures/hour
$\lambda_2 = 0.006$ failures/hour
$\lambda_3 = 0.002$ failures/hour
$\lambda_4 = 0.003$ failures/hour

Calculate the vehicle/transit system mean time to failure.

By substituting the given data values into Equation (6.24), we get

$$MTTF_{vs} = \frac{(0.004 + 0.006 + 0.003)}{(0.004 + 0.002)(0.006 + 0.003)}$$

$$= 240.74 \text{ hours}$$

Thus, the vehicle/transit system mean time to failure is 240.74 hours.

6.4 Model III

This mathematical model represents a four-state transit system in which a vehicle can be in any one of the four states: vehicle operating normally in the field, vehicle failed safely in the field, vehicle failed with accident in the field, and failed vehicle in the repair workshop. The failed vehicle is taken to the repair workshop from the field. The repaired vehicle is put back into its normal operation.

The system state-space diagram is shown in Figure 6.3. The numerals in boxes and circles denote system states.

The following assumptions are associated with the model:

- Vehicle safe failure, accident failure, towing, and repair rates are constant.
- Vehicle failures occur independently.
- A repaired vehicle is as good as new.

The following symbols are associated with the model state-space diagram:

i = ith state of the vehicle/transit system, where $i = 0$ (vehicle operating normally in the field), $i = 1$ (vehicle failed safely in the field), $i = 2$

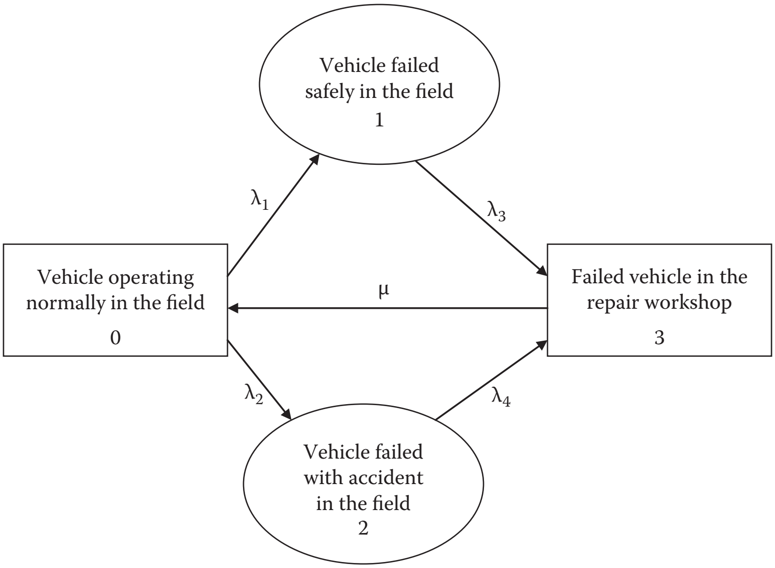

FIGURE 6.3
State space diagram for Model III.

(vehicle failed with accident in the field), i = 3 (failed vehicle in the repair workshop)

λ_1 = vehicle fail-safe constant failure rate
λ_2 = vehicle fail-accident constant failure rate
λ_3 = vehicle constant towing rate from state 1
λ_4 = vehicle constant towing rate from state 2
μ = vehicle constant repair rate
$P_i(t)$ = probability that the vehicle/transit system is in state i at time t, for $i = 0,1,2,3$

Using the Markov method described in Chapter 4 and Figure 6.3, we write down the following equations [4]:

$$\frac{dP_0(t)}{dt} + (\lambda_1 + \lambda_2)P_0(t) = \mu P_3(t) \tag{6.25}$$

$$\frac{dP_1(t)}{dt} + \lambda_3 P_1(t) = \lambda_1 P_0(t) \tag{6.26}$$

$$\frac{dP_2(t)}{dt} + \lambda_4 P_2(t) = \lambda_2 P_0(t) \tag{6.27}$$

$$\frac{dP_3(t)}{dt} + \mu P_3(t) = \lambda_3 P_1(t) + \lambda_4 P_2(t) \tag{6.28}$$

At time $t = 0$, $P_0(0) = 1$, $P_1(0) = 0$, $P_2(0) = 0$, and $P_3(0) = 0$.

By solving Equations (6.25)–(6.28), we obtain the following steady-state probability equations [4]:

$$P_0 = \left[1 + \frac{\lambda_1}{\lambda_3} + \frac{\lambda_2}{\lambda_4} + \frac{(\lambda_1 + \lambda_2)}{\mu}\right]^{-1} \tag{6.29}$$

$$P_1 = \frac{\lambda_1 P_0}{\lambda_3} \tag{6.30}$$

$$P_2 = \frac{\lambda_2 P_0}{\lambda_4} \tag{6.31}$$

$$P_3 = \frac{(\lambda_1 + \lambda_2) P_0}{\mu} \tag{6.32}$$

where

P_0, P_1, P_2, and P_3 = steady-state probabilities of the vehicle/transit system being in states 0, 1, 2, and 3, respectively

The vehicle/transit system steady state availability is given by

$$AV_{vs} = P_0 \tag{6.33}$$

where

AV_{vs} = vehicle transit system steady-state availability

By setting $\mu = 0$ in Equations (6.25)–(6.28) and then solving the resulting equations, we get

$$R_{sv}(t) = e^{-(\lambda_1 + \lambda_2)t} \tag{6.34}$$

where

$R_{vs}(t)$ = vehicle/transit system reliability at time t

The vehicle/transit system mean time to failure is given by [5]:

$$\begin{aligned} MTTF_{vs} &= \int_o^\infty R_{vs}(t)dt \\ &= \int_0^\infty e^{-(\lambda_1 + \lambda_2)t} \\ &= \frac{1}{(\lambda_1 + \lambda_2)} \end{aligned} \tag{6.35}$$

where

$MTTF_{vs}$ = vehicle/transit system mean time to failure

Example 6.3

Assume that a vehicle fail-safe and fail-with-accident failure rates are 0.0008 failures/hour and 0.0001 failures/hour, respectively. Calculate the vehicle reliability during an 8-hour mission and mean time to failure.

By substituting the specified data values into Equation (6.34), we get

$$R_{vs}(8) = e^{-(0.0008+0.0001)(8)}$$

$$= 0.9928$$

Using the given data values in Equation (6.35) yields

$$MTTF_{vs} = \frac{1}{(0.0008+0.0001)}$$

$$= 1111.1 \text{ hours}$$

Thus, the vehicle reliability and mean time to failure are 0.9928 and 1111.1 hours, respectively.

6.5 Model IV

This mathematical model is concerned with two identical vehicles being used in a day-to-day environment in the field. The two-vehicle system can be in any of the following four states:

- Both vehicles operating successfully in the field
- One vehicle operating successfully and the other failed in the field
- Both vehicles failed in the field
- Failed vehicle(s) in the repair workshop

When one or both vehicles fail in the field, an attempt is made to repair the failed vehicle or vehicles back to fully operational state (i.e., where both vehicles are operating successfully). Furthermore, if both failed vehicles cannot be repaired simultaneously in the field, then an attempt is made to repair any one of the failed vehicles. In both cases, if repair attempts are unsuccessful in the field, then the vehicles are towed to the repair workshop.

The model/system state-space diagram is shown in Figure 6.4. The numeral and the single and double letters in boxes and the single letter in the circle denote system states.

The following assumptions are associated with the model:

- All failures occur independently.
- Failure, partial failure, towing, and repair rates are constant.

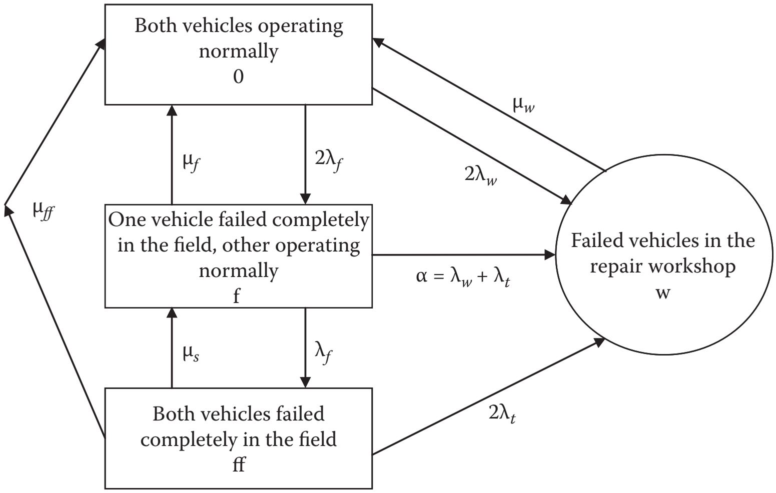

FIGURE 6.4
State space diagram for Model IV.

- Repaired vehicle or vehicles are as good as new.
- Partially failed vehicle is driven to the repair workshop.

The following symbols are associated with the model state-space diagram:

i = ith state of the system, where i = 0 (both vehicles operating normally), i = f (one vehicle failed completely in the field, other operating normally), i = ff (both vehicles failed completely in the field), i = w (failed vehicle(s) in the repair workshop)

$P_i(t)$ = probability that the system is in state i at time t, for i = 0, f, ff, w

λ_f = vehicle constant failure rate

λ_w = constant rate of the vehicle failed partially in the field (the partially failed vehicle is driven to the repair workshop for repair)

λ_t = constant towing rate of the completely failed vehicle

μ_i = ith constant repair rate, where i = s (from state ff to state f), i = f (from state f to state 0), i = ff (from state ff to state 0), i = w (from state w to state 0)

Using the Markov method described in Chapter 4 and Figure 6.4, we write down the following equations [6]:

$$\frac{dP_0(t)}{dt} + (2\lambda_f + \lambda_w)P_0(t) = \mu_w P_w(t) + \mu_f P_f(t) + \mu_{ff} P_{ff}(t) \tag{6.36}$$

$$\frac{dP_w(t)}{dt} + \mu_w P_w(t) = 2\lambda_w P_0(t) + \alpha P_f(t) + 2\lambda_t P_{ff}(t) \tag{6.37}$$

$$\frac{dP_f(t)}{dt} + (\lambda_f + \alpha + \mu_f)P_f(t) = \mu_s P_{ff}(t) + 2\lambda_f P_0(t) \tag{6.38}$$

$$\frac{dP_{ff}(t)}{dt} + (2\lambda_t + \mu_s + \mu_{ff})P_{ff}(t) = \lambda_f P_f(t) \tag{6.39}$$

At time $t = 0$, $P_0(0) = 1$, $P_w(0) = 0$, $P_f(0) = 0$, and $P_{ff}(0) = 0$.

By solving Equations (6.36)–(6.39), we get the following steady-state probability equations [6]:

$$P_0 = (A.\mu_w) / \left[A(2\lambda_f + 2\lambda_w + \mu_w) + (\mu_w - \mu_f)(2\lambda_t + \mu_s + \mu_{ff})2\lambda_f + 2\lambda_f^2(\mu_w - \mu_{ff}) \right] \tag{6.40}$$

where

$$\text{A} = (\lambda_f + \alpha + \mu_f)(2\lambda_t + \mu_s + \mu_{ff}) - \mu_s\lambda_f \tag{6.41}$$

$$P_w = 1 - \left[\frac{A + 2\lambda_f(2\lambda_t + \mu_s + \mu_{ff}) + 2\lambda_f^2}{A} \right] P_0 \tag{6.42}$$

$$P_f = \frac{2\lambda_f P_0(2\lambda_t + \mu_s + \mu_{ff)}}{(\lambda_f + \alpha + \mu_f)(2\lambda_t + \mu_s + \mu_{ff}) - \mu_s\lambda_f} \tag{6.43}$$

$$P_{ff} = (2\lambda_f^2 P_0) / (\lambda_f + \alpha + \mu_f)(2\lambda_t + \mu_s + \mu_{ff}) - \mu_s\lambda_f \tag{6.44}$$

where

P_0, P_w, P_f, and P_{ff} = steady-state probabilities of the system being in states 0, w, f, and ff, respectively

6.6 Model V

This mathematical model represents a system in which a vehicle is operating in alternating weather (e.g., normal and stormy). The vehicle can fail operating either in normal or stormy weather. The failed vehicle is repaired back to both its operating states. The system state-space diagram is shown in Figure 6.5. The numerals in boxes and a circle denote system states.

The following assumptions are associated with the model:

- Vehicle failure and repair rates are constant.
- Alternating weather transition rates (i.e., from normal weather state to stormy weather state and vice versa) are constant.

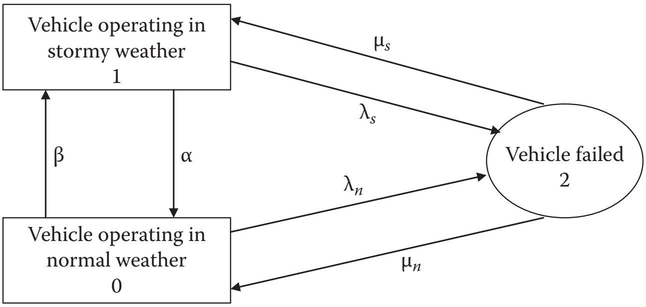

FIGURE 6.5
State space diagram for Model V.

- A repaired vehicle is as good as new.
- Vehicle failures occur independently.

The following symbols are associated with the model:

i = ith state of the vehicle/system, where $i = 0$ (vehicle operating in normal weather), $i = 1$ (vehicle operating in stormy weather), $i = 2$ (vehicle failed)
λ_n = is the vehicle constant failure rate for normal weather state
λ_s = vehicle constant failure rate for stormy weather state
β = weather constant changeover rate from state 0 to state 1
α = weather constant changeover rate from state 1 to state 0
μ_n = vehicle constant repair rate (normal weather) from state 2 to state 0
μ_s = vehicle constant repair rate (stormy weather) from state 2 to state 1
$P_i(t)$ = probability that the system is in state i at time t, for $i = 0,1,2$

Using the Markov method described in Chapter 4 and Figure 6.5, we write down the following equations [7]:

$$\frac{dP_0(t)}{dt} + (\beta + \lambda_n)P_0(t) = \alpha P_1(t) + \mu_n P_2(t) \tag{6.45}$$

$$\frac{dP_1(t)}{dt} + (\alpha + \lambda_s)P_1(t) = \beta P_0(t) + \mu_s P_2(t) \tag{6.46}$$

$$\frac{dP_2(t)}{dt} + (\mu_n + \mu_s)P_2(t) = \lambda_n P_0(t) + \lambda_s P_1(t) \tag{6.47}$$

At time $t = 0$, $P_0(0) = 1$, $P_1(0) = 0$, and $P_2(0) = 0$.

By solving Equations (6.45)–(6.47), we obtain the following steady-state probability equations [7]:

$$P_0 = A_1 / C_1 C_2 \tag{6.48}$$

where

$$A_1 = \mu_n\alpha + \lambda_s\mu_n + \alpha\mu_s \tag{6.49}$$

$$C_1, C_2 = \frac{-D \pm \left[D^2 - 4(A_1 + A_2 + A_3)\right]^{1/2}}{2} \tag{6.50}$$

$$A_2 = \beta\lambda_s + \alpha\mu_n + \lambda_n\lambda_s \tag{6.51}$$

$$A_3 = \beta\mu_n + \beta\mu_s + \lambda_n\mu_s \tag{6.52}$$

$$\mathrm{D} = \alpha + \mu_n + \mu_s + \beta + \lambda_n + \lambda_s \tag{6.53}$$

$$P_1 = A_3 / C_1C_2 \tag{6.54}$$

$$P_2 = A_2 / C_1C_2 \tag{6.55}$$

where

P_0, P_1, and P_2 = steady-state probabilities of the vehicle/system being in states 0, 1, and 2, respectively

The vehicle steady-state availability in both types of weather is given by

$$A_{vss} = P_0 + P_1 \tag{6.56}$$

where

A_{vss} = vehicle steady state availability in both types of weather

By setting $\mu_{\mathrm{n}} = \mu_{\mathrm{s}} = 0$ in Equations (6.45)–(6.47) and then solving the resulting equations and using the work of Dhillon [5, 7], we get

$$\mathrm{MTTF_v} = \lim_{s\to 0} R_v(s) = \lim_{s\to 0}\{P_0(s) + P_1(s)\}$$

$$= \frac{\lambda_s + \beta + \alpha}{(\lambda_n + \beta)(\lambda_s + \alpha) - \beta\alpha} \tag{6.57}$$

where

$\mathrm{MTTF_v}$ = vehicle mean time to failure
s = Laplace transform variable
$R_{\mathrm{v}}(s)$ = Laplace transform of the vehicle reliability
$P_0(s)$ = Laplace transform of the probability that the vehicle is in state 0
$P_1(s)$ = Laplace transform of the probability that the vehicle is in state 1

Example 6.4

Assume that in Equation (6.57), we have the following specified data values:

λ_{n} = 0.0004 failures/hour
λ_{s} = 0.0001 failures/hour

$\beta = 0.0001$ transitions/hour
$\alpha = 0.0002$ transitions/hour

Calculate the vehicle mean time to failure.

By substituting the given data values into Equation (6.57), we get

$$MTTF_v = \frac{(0.0001+0.0001+0.0002)}{(0.0004+0.0001)(0.0001+0.0002)-(0.0001)(0.0002)}$$

$$= 3076.92 \text{ hours}$$

Thus, the vehicle mean time to failure is 3,076.92 hours.

6.7 Model VI

This mathematical model represents a system in which a vehicle is operating in alternating weather (e.g., normal and stormy). The vehicle can fail due to an accident or a hardware failure while operating either in normal or stormy weather. The failed vehicle from both failed states is repaired back to both its operating states. The system state-space diagram is shown in Figure 6.6 [7]. The numerals in boxes and circles denote system states.

The following assumptions are associated with the model:

- All vehicle failure and repair rates are constant.
- Vehicle failures occur independently.
- Alternating weather transition rates (i.e., from normal weather state to stormy weather state and vice versa) are constant.
- A repaired vehicle is as good as new.

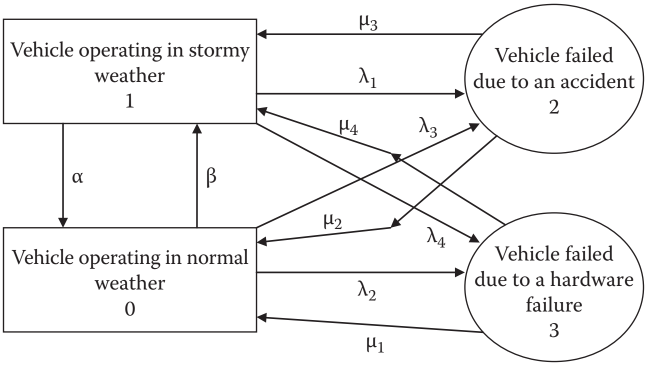

FIGURE 6.6
State space diagram for Model VI.

The following symbols are associated with the model:

i = ith state of the vehicle/system, where $i = 0$ (vehicle operating in normal weather), $i = 1$ (vehicle operating in stormy weather), $i = 2$ (vehicle failed due to an accident), $i = 3$ (vehicle failed due to a hardware failure)

λ_i = vehicle ith constant failure rate, where $i = 1$ (from state 1 to state 2), $i = 2$ (from state 0 to state 3), $i = 3$ (from state 0 to state 2), $i = 4$ (from state 1 to state 3)

μ_i = vehicle ith constant repair rate, where $i = 1$ (from state 3 to state 0), $i = 2$ (from state 2 to state 0), $i = 3$ (from state 2 to state 1), $i = 4$ (from state 3 to state 1)

β = weather constant changeover rate from state 0 to state 1

α = weather constant changeover rate from state 1 to state 0

$P_i(t)$ = probability that the system/vehicle is in state i at time t, for $i = 0,1,2,3$

Using the Markov method described in Chapter 4 and Figure 6.6, we write down the following equations [7]:

$$\frac{dP_0(t)}{dt} + (\beta + \lambda_2 + \lambda_3)P_0(t) = \alpha_1 P_1(t) + \mu_2 P_2(t) + \mu_1 P_3(t) \tag{6.58}$$

$$\frac{dP_1(t)}{dt} + (\alpha + \lambda_1 + \lambda_4)P_1(t) = \beta P_0(t) + \mu_3 P_2(t) + \mu_4 P_3(t) \tag{6.59}$$

$$\frac{dP_2(t)}{dt} + (\mu_3 + \mu_2)P_2(t) = \lambda_1 P_1(t) + \lambda_3 P_0(t) \tag{6.60}$$

$$\frac{dP_3(t)}{dt} + (\mu_1 + \mu_4)P_3(t) = \lambda_2 P_0(t) + \lambda_4 P_1(t) \tag{6.61}$$

At time $t = 0$, $P_0(0) = 1$, $P_1(0) = 0$, $P_2(0) = 0$, and $P_3(0) = 0$.

By solving Equations (6.58)–(6.61), we get the following steady-state probability equations [7]:

$$P_0 = \mu_1\mu_2 A / \left[A\mu_1\mu_2 + \beta\mu_1\mu_2 + \beta\lambda_1\mu_1 + A\lambda_3\mu_1 + A\mu_2\lambda_2 + \beta\lambda_4\mu_2\right] \tag{6.62}$$

where

$A = \alpha + \lambda_1 + \lambda_4$

$$P_1 = \beta P_0 / A \tag{6.63}$$

$$P_2 = P_0\left[\frac{\beta\lambda_1}{A\mu_2} + \frac{\lambda_3}{\mu_2}\right] \tag{6.64}$$

$$P_3 = P_0\left[\frac{\lambda_2}{\mu_1} + \frac{\beta\lambda_4}{A\mu_1}\right] \tag{6.65}$$

where

P_0, P_1, P_2, and P_3 = steady-state probabilities of the vehicle being in states 0, 1, 2, and 3, respectively

The vehicle steady-state availability in both types of weather is given by

$$A_{vss} = P_0 + P_1 \tag{6.66}$$

where

A_{vss} = vehicle steady-state availability in both types of weather

6.8 Model VII

This mathematical model represents a system in which a vehicle is operating in alternating weather (e.g., normal and stormy). In either type of weather the vehicle may fail completely or partially. Furthermore, the partially failed vehicle can fail completely. The completely failed vehicle is repaired back to its fully operational state in alternating weather condition.

The system state-space diagram is shown in Figure 6.7. The numerals in boxes and circles denotes system states. The following assumptions are associated with the model:

- Vehicle failures occur independently.
- Alternating weather transition rates (i.e., from normal weather state to stormy weather state and vice versa) are constant.

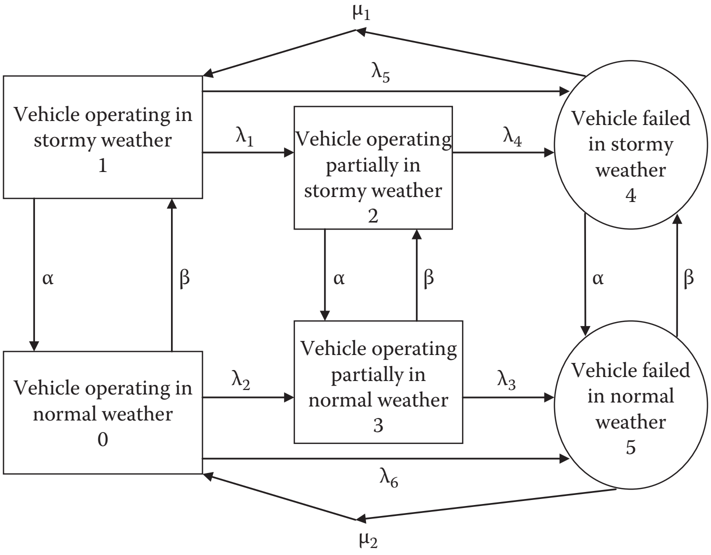

FIGURE 6.7
State space diagram for Model VII.

- All vehicle failure and repair rates are constant.
- A repaired vehicle is as good as new.

The following symbols are associated with the model:

i = ith state of the vehicle/system, where $i = 0$ (vehicle operating in normal weather), $i = 1$ (vehicle operating in stormy weather), $i = 2$ (vehicle operating partially in stormy weather), $i = 3$ (vehicle operating partially in normal weather), $i = 4$ (vehicle failed in stormy weather), $i = 5$ (vehicle failed in normal weather)

λ_i = vehicle ith constant failure rate, where $i = 1$ (from state 1 to state 2), $i = 2$ (from state 0 to state 3), $i = 3$ (from state 3 to state 5), $i = 4$ (from state 2 to state 4), $i = 5$ (from state 1 to state 4), $i = 6$ (from state 0 to state 5)

μ_i = vehicle ith constant repair rate, where $i = 1$ (from state 4 to state 1), $i = 2$ (from state 5 to state 0)

α = weather constant changeover rate from state 1 to state 0

β = weather constant changeover rate from state 0 to state 1

$P_i(t)$ = probability that the system/vehicle is in state i at time t, for $i = 0,1,2,3,4,5$

Using the Markov method described in Chapter 4 and Figure 6.7, we write down the following equations [7]:

$$\frac{dP_0(t)}{dt} + (\beta + \lambda_2 + \lambda_6)P_0(t) = \alpha P_1(t) + \mu_2 P_5(t) \tag{6.67}$$

$$\frac{dP_1(t)}{dt} + (\alpha + \lambda_1 + \lambda_5)P_1(t) = \beta P_0(t) + \mu_1 P_4(t) \tag{6.68}$$

$$\frac{dP_2(t)}{dt} + (\alpha + \lambda_4)P_2(t) = \lambda_1 P_1(t) + \beta P_3(t) \tag{6.69}$$

$$\frac{dP_3(t)}{dt} + (\lambda_3 + \beta)P_3(t) = \alpha P_2(t) + \lambda_2 P_0(t) \tag{6.70}$$

$$\frac{dP_4(t)}{dt} + (\alpha + \mu_1)P_4(t) = \beta P_5(t) + \lambda_5 P_1(t) + \lambda_4 P_2(t) \tag{6.71}$$

$$\frac{dP_5(t)}{dt} + (\beta + \mu_2)P_5(t) = \alpha P_4(t) + \lambda_3 P_3(t) + \lambda_6 P_0(t) \tag{6.72}$$

At time $t = 0$, $P_0(0) = 1$, $P_1(0) = 0$, $P_2(0) = 0$, $P_3(0) = 0$, $P_4(0) = 0$, and $P_5(0) = 0$.

By solving Equations (6.67)–(6.72), we obtain the following steady-state probability equations [7]:

$$P_0 = \left[1 + \sum_{i=1}^{5} A_i\right]^{-1} \tag{6.73}$$

where

$$A_1 = \beta / D \tag{6.74}$$

$$A_2 = \frac{\beta\lambda_1}{DF} + \frac{\beta\lambda_2}{G} + \frac{\alpha\beta^2\lambda_1}{DFG} \tag{6.75}$$

$$A_3 = \frac{F\lambda_2}{G} + \frac{\alpha\beta\lambda_1}{GD} \tag{6.76}$$

$$A_4 = \frac{\beta}{\alpha\mu_2}\left[\beta + \lambda_2 + \lambda_6\right] - \frac{\beta^2}{D\mu_2} + \frac{\beta\lambda_5}{\alpha D} + \frac{\beta\lambda_1\lambda_4}{\alpha DF} + \frac{\beta\lambda_2\lambda_4}{\alpha G} + \frac{\beta^2\lambda_1\lambda_4}{GDF} \tag{6.77}$$

$$A_5 = \left[\frac{\beta + \lambda_2 + \lambda_6}{\mu_2}\right] - \frac{\alpha\beta}{D\mu_2} \tag{6.78}$$

$$D = \alpha + \lambda_1 + \lambda_5 \tag{6.79}$$

$$G = (\lambda_3 + \beta)F - \alpha\beta \tag{6.80}$$

$$\mathrm{F} = (\alpha + \lambda_4) \tag{6.81}$$

$$P_1 = P_0 A_1 \tag{6.82}$$

$$P_2 = P_0 A_2 \tag{6.83}$$

$$P_3 = P_0 A_3 \tag{6.84}$$

$$P_4 = P_0 A_4 \tag{6.85}$$

$$P_5 = P_0 A_5 \tag{6.86}$$

The vehicle steady-state availability in both types of weather is given by

$$A_{vss} = P_0 + P_1 + P_2 + P_3 \tag{6.87}$$

where

A_{vss} = vehicle steady state availability in both types of weather

By setting $\mu_1 = \mu_2 = 0$ in Equations (6.67)–(6.72) and then solving the resulting equations and using the work of Dhillon [5, 7], we obtain

$$MTTF_v = \lim_{s \to 0} R(s) = \lim_{s \to 0}\left[P_0(s) + P_1(s) + P_2(s) + P_3(s)\right]$$

$$= \frac{(D+\beta)}{B_1} + \frac{(\beta\lambda_1)}{FB_1} + \frac{(D\beta\lambda_2)}{B_1B_2} + \frac{(\alpha\beta^2\lambda_1)}{FB_1B_2} + \frac{(DF\lambda_2)}{B_1B_2} + \frac{(BF\alpha\lambda_1)}{FB_1B_2} \tag{6.88}$$

where

$$B_1 = DH - \alpha\beta \tag{6.89}$$

$$B_2 = (\lambda_3 + \beta)F - \alpha\beta \tag{6.90}$$

$$H = \beta + \lambda_2 + \lambda_6 \tag{6.91}$$

6.9 Model VIII

This mathematical model represents a system composed of *n* independent and identical vehicles operating in parallel. At least one vehicle must work normally for the system success. Whenever a vehicle fails, it is towed to the repair workshop for repair. The fully repaired vehicle is put back into operation. The system state-space diagram is shown in Figure 6.8. The numerals and a single letter in boxes and circles denote system states.

The following assumptions are associated with the model:

- Vehicle failures occur independently.
- Vehicle failure, repair, and towing rates are constant.

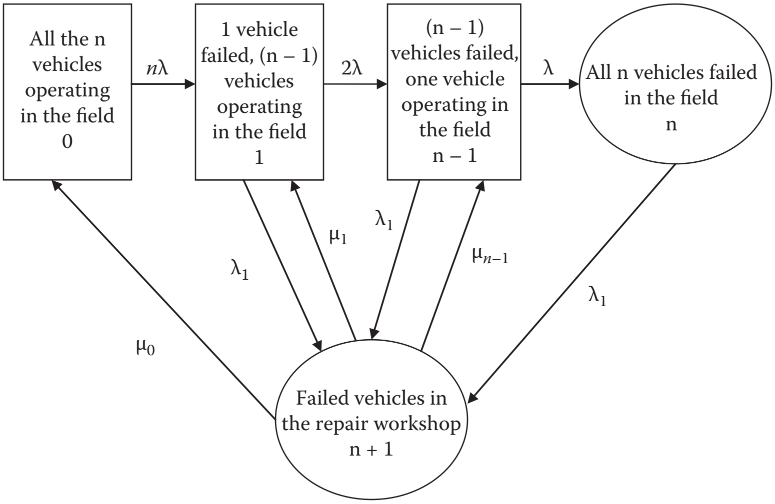

FIGURE 6.8
State space diagram for Model VIII.

- The system is composed of a fleet of n identical vehicles.
- The system is considered operational when at least one vehicle is operating.
- A repaired vehicle is as good as new.

The following symbols are associated with the model:

i = ith state of the system, where $i = 0$ (all the n vehicles operating in the field), $i = 1$ (1 vehicle failed, $[n-1]$ vehicles operating in the field), $i = (n-1)$ ($[n-1]$ vehicles failed, one vehicle operating in the field), $i = n$ (all n vehicles failed in the field), $i = (n+1)$ (failed vehicles in the repair workshop)

λ = vehicle constant failure rate

n = number of identical vehicles in the system

λ_i = vehicle constant towing rate

μ_i = transit system constant repair rate from state $(n+1)$ to state i, for $i = 0,1,2,\ldots,(n-1)$

$P_i(t)$ = probability that the transit system is in state i at time t, for $i = 0,1,2,\ldots,(n+1)$

Using the Markov method described in Chapter 4 and Figure 6.8, we write down the following equations [8]:

$$\frac{dP_0(t)}{dt} + n\lambda P_0(t) = \mu_0 P_{n+1}(t) \tag{6.92}$$

$$\frac{dP_1(t)}{dt} + \left[(n-1)\lambda + \lambda_1\right]P_1(t) = \mu_1 P_{n+1}(t) + n\lambda P_0(t) \tag{6.93}$$

$$\frac{dP_2(t)}{dt} + \left[(n-2)\lambda + \lambda_1\right]P_2(t) = \mu_2 P_{n+1}(t) + (n-1)\lambda P_1(t) \tag{6.94}$$

$$\vdots$$

$$\frac{dP_{n-1}(t)}{dt} + (\lambda + \lambda_1)P_{n-1}(t) = \mu_{n-1} P_{n+1}(t) + 2\lambda P_{n-2}(t) \tag{6.95}$$

$$\frac{dP_n(t)}{dt} + \lambda_1 P_n(t) = \lambda P_{n-1}(t) \tag{6.96}$$

$$\frac{dP_{n+1}(t)}{dt} + \left(\sum_{i=0}^{n-1}\mu_i\right)P_{n+1}(t) = \lambda_1\left[\sum_{i=1}^{n}P_i(t)\right] \tag{6.97}$$

At time $t = 0$, $P_0(0) = 1$, and all other initial condition probabilities are equal to zero.

By solving Equations (6.92)–(6.97), we get the following steady-state probability equations [8]:

$$P_i = \frac{a_i}{b_i} P_{n+1}, \text{ for } i = 0,1,2,\ldots,n \tag{6.98}$$

where

$$P_{n+1} = \frac{\lambda_1}{\sum_{i=0}^{n-1} \mu_i} \left[1 + \frac{\lambda_1}{\sum_{i=0}^{n-1} \mu_i} \left(1 + \frac{a_0}{b_0} \right) \right]^{-1} \tag{6.99}$$

$$a_0 = \mu_0 \tag{6.100}$$

$$a_1 = \mu_0 + \mu_1 \tag{6.101}$$

$$a_i = \mu_i b_{i-1} + [(n - i + 1)\lambda] a_{i-1}, \text{ for } i = 2,3,\ldots,n - 1 \ (n = 3,4,\ldots) \tag{6.102}$$

$$a_n = \lambda a_{n-1} \tag{6.103}$$

$$b_0 = n\lambda \tag{6.104}$$

$$b_1 = (n - 1)\lambda + \lambda_1 \tag{6.105}$$

$$b_i = b_{i-1}[(n - i)\lambda + \lambda_1], \text{ for } i = 2,3,\ldots,n \tag{6.106}$$

P_i = steady-state probability that the transit system is in state i, for $i = 0,1,2,\ldots,(n + 1)$

The steady-state operational availability (i.e., the probability that at least one vehicle is operating) of the transit system is given by Dhillon and Rayapati [8].

$$AV_{ss} = \sum_{i=0}^{n-1} P_i \tag{6.107}$$

where

AV_{ss} = transit system steady-state operational availability

Example 6.5

For $n = 2$, using Equations (6.98)–(6.107), obtain expressions for steady-state probabilities and transit system steady-state operational availability.

By substituting the given data value into Equations (6.98)–(6.107), we get

$$P_0 = \mu_0 P_2 / \lambda \tag{6.108}$$

$$P_1 = \mu_0 P_2 / \lambda_1 \tag{6.109}$$

$$P_2 = \frac{\lambda_1 \lambda}{\mu_0 \lambda + \lambda_1(\lambda + \mu_0)} \tag{6.110}$$

and

$$AV_{ss} = \frac{\lambda_1 \mu_0}{\lambda \mu_0 + \lambda_1(\lambda + \mu_0)} \tag{6.111}$$

Thus, Equations (6.108)–(6.111) are the expressions for steady-state probabilities and transit system availability.

Example 6.6

Assume that in Equation (6.111) we have $\lambda = 0.0004$ failures/hour, $\lambda_1 = 0.003$/hour, and $\mu_0 = 0.08$ repairs/hour. Calculate the value of AV_{ss} (i.e., transit system steady-state availability).

By substituting the given data into Equation (6.111), we get

$$\begin{aligned} AV_{ss} &= \frac{(0.003)(0.08)}{(0.0004)(0.08) + (0.003)\left[(0.0004 + 0.08)\right]} \\ &= 0.8785 \end{aligned}.$$

Thus, the value of AV_{ss} is 0.8785.

6.10 Model IX

This mathematical model represents a transit system that can fail either due to hardware failures or human errors. A truck is a typical example of such a system. The failed transit system is towed to the repair workshop for repair. The system state-space diagram is shown in Figure 6.9. The numerals in box and circles denote system states.

The following assumptions are associated with the model:

- Failure and towing rates are constant.
- The transit system can fail completely either due to human errors or hardware failures.
- Human errors and failures occur independently.

The following symbols are associated with the model:

i = ith state of the transit system, where $i = 0$ (transit system operating normally), $i = 1$ (transit system failed in the field due to a hardware

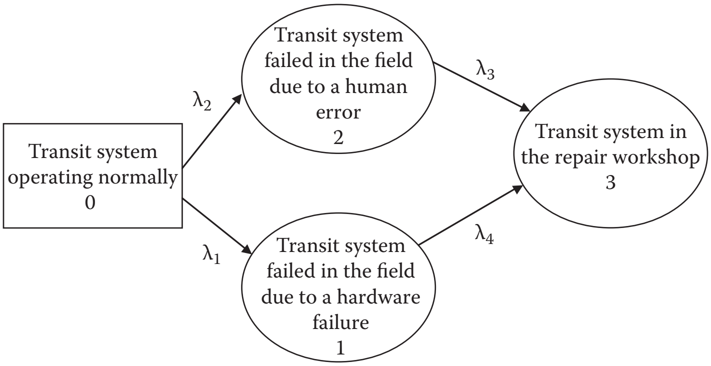

FIGURE 6.9
State space diagram for Model IX.

failure), $i = 2$ (transit system failed in the field due to a human error), $i = 3$ (transit system in the repair workshop)

λ_1 = transit system constant hardware failure rate
λ_2 = transit system constant failure rate due to human errors
λ_3 = transit system constant towing rate from state 2 to state 3
λ_4 = transit system constant towing rate from state 1 to state 3
$P_i(t)$ = probability that the transit system is in state i at time t, for $i = 0,1,2,3$

Using the Markov method described in Chapter 4 and Figure 6.9, we write down the following equations [9–11]:

$$\frac{dP_0(t)}{dt} + (\lambda_1 + \lambda_2)P_0(t) = 0 \tag{6.112}$$

$$\frac{dP_1(t)}{dt} + \lambda_4 P_1(t) = \lambda_1 P_0(t) \tag{6.113}$$

$$\frac{dP_2(t)}{dt} + \lambda_3 P_2(t) = \lambda_1 P_0(t) \tag{6.114}$$

$$\frac{dP_3(t)}{dt} = \lambda_3 P_2(t) + \lambda_4 P_1(t) \tag{6.115}$$

At time $t = 0$, $P_0(0) = 1$, $P_1(0) = 0$, $P_2(0) = 0$, and $P_3(0) = 0$.

By solving Equations (6.112)–(6.115), we obtain the following state probability equations [9–11]:

$$P_0(t) = e^{-at} \tag{6.116}$$

where

$$a = \lambda_1 + \lambda_2$$

$$P_1(t) = c_2(e^{-at} - e^{-\lambda_4 t}). \tag{6.117}$$

where

$$c_2 = \frac{\lambda_1}{(\lambda_4 - a)} \tag{6.118}$$

$$P_2(t) = c_1(e^{-at} - e^{-\lambda_3 t}) \tag{6.119}$$

where

$$c_1 = \frac{\lambda_2}{(\lambda_3 - a)} \tag{6.120}$$

$$P_3(t) = 1 + c_1 e^{-\lambda_3 t} + c_2 e^{-\lambda_4 t} + c_3 e^{-(\lambda_1+\lambda_2)t} \tag{6.121}$$

where

$$c_3 = -\left[c_1\lambda_3 + c_2\lambda_4\right]/a \tag{6.122}$$

The transit system reliability is given by

$$R_{ts}(t) = P_0(t) = e^{-at} = e^{-(\lambda_1+\lambda_2)t} \tag{6.123}$$

where

$R_{ts}(t)$ = transit system reliability at time t

The transit system mean time to failure is given by [5, 9–11]

$$\begin{aligned} MTTF_{ts} &= \int_0^{\infty} R_{ts}(t)dt \\ &= \int_0^{\infty} e^{-(\lambda_1+\lambda_2)t} dt \\ &= \frac{1}{\lambda_1 + \lambda_2} \end{aligned} \tag{6.124}$$

where

MTTF_{ts} = transit system mean time to failure

Example 6.7

A transit system hardware failure and failure due to human error rates are 0.0002 failures/hour and 0.0001 failures/hour, respectively. Calculate the transit system reliability during a 12-hour mission.

By substituting the specified data values into Equation (6.123), we get

$$\begin{aligned} R_{ts}(12) &= e^{-(0.0002+0.0001)(12)} \\ &= 0.9964 \end{aligned}$$

Thus, the transit system reliability is 0.9964.

6.11 Model X

This mathematical model is basically the same as model IX, but with one exception, i.e., the failed transit system is repaired. More specifically, when the transit system fails in the field, repair is attempted in the field environment. If it cannot be repaired, the failed transit system is towed to the repair workshop for repair.

The system state-space diagram is shown in Figure 6.10. The numerals in box and circles denote system states. The following assumptions are associated with the model:

- Human errors and failures occur independently.
- Failure, towing, and repair rates are constant.
- The transit system can fail completely either due to human errors or hardware failures.
- The repaired transit system is as good as new.

The following symbols are associated with the model:

μ_1 = transit system constant repair rate when failed in the field due to a hardware failure

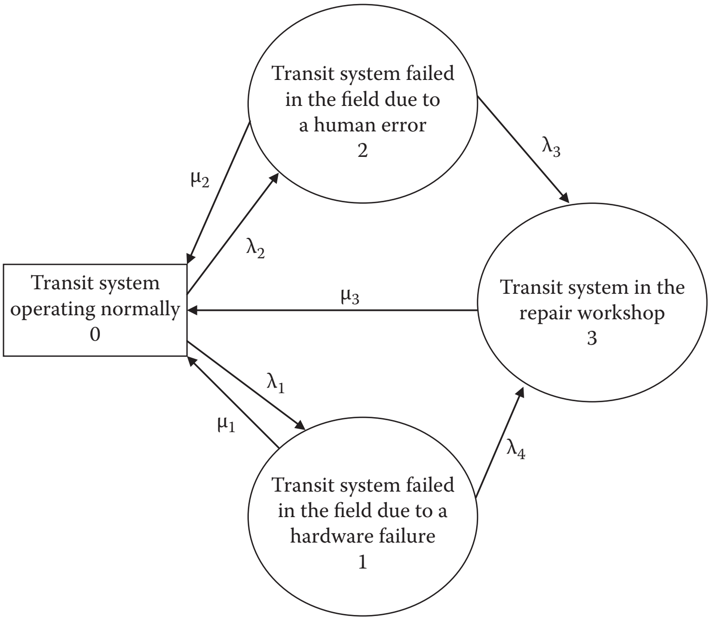

FIGURE 6.10
State space diagram for Model X.

μ_2 = transit system constant repair rate when failed in the field due to a human error

μ_3 = transit system constant repair rate from the repair workshop

λ_1 = transit system constant hardware failure rate

λ_2 = transit system constant failure rate due to human errors

λ_3 = transit system constant towing rate from state 2 to state 3

λ_4 = transit system constant towing rate from state 1 to state 3

i = ith state of the transit system, where $i = 0$ (transit system operating normally), $i = 1$ (transit system failed in the field due to a hardware failure), $i = 2$ (transit system failed in the field due to a human error), $i = 3$ (transit system in the repair workshop)

$P_i(t)$ = probability that the transit system is in state i at time t, for $i = 0,1,2,3$

Using the Markov method described in Chapter 4 and Figure 6.10, we write down the following equations [9–11]:

$$\frac{dP_0(t)}{dt} + (\lambda_1 + \lambda_2)P_0(t) = \mu_2 P_2(t) + \mu_1 P_1(t) + \mu_3 P_3(t) \tag{6.125}$$

$$\frac{dP_1(t)}{dt} + (\lambda_4 + \mu_1)P_1(t) = \lambda_1 P_0(t) \tag{6.126}$$

$$\frac{dP_2(t)}{dt} + (\lambda_3 + \mu_2)P_2(t) = \lambda_2 P_0(t) \tag{6.127}$$

$$\frac{dP_3(t)}{dt} + \mu_3 P_3(t) = \lambda_3 P_2(t) + \lambda_4 P_1(t) \tag{6.128}$$

At time $t = 0$, $P_0(0) = 1$, $P_1(0) = 0$, $P_2(0) = 0$, and $P_3(0) = 0$.

By solving Equations (6.125)–(6.128), we get the following steady-state probability equations [9–11]:

$$P_0 = X / Y \tag{6.129}$$

$$P_i = n_i P_0, \text{. for } i = 1,2,3 \tag{6.130}$$

where

$$X = \mu_3(\lambda_3 + \mu_2)(\lambda_4 + \mu_1) \tag{6.131}$$

$$Y = (\lambda_3 + \mu_2)\left[\mu_3(\lambda_4 + \mu_1) + \lambda_1(\mu_3 + \lambda_4)\right] + \lambda_2(\lambda_4 + \mu_1)(\lambda_3 + \mu_3) \tag{6.132}$$

$$n_1 = \lambda_2 / (\lambda_3 + \mu_2) \tag{6.133}$$

$$n_2 = \lambda_1 / (\lambda_4 + \mu_1) \tag{6.134}$$

$$n_3 = \frac{\left[\lambda_2\lambda_3(\lambda_4 + \mu_1) + \lambda_1\lambda_4(\lambda_3 + \mu_2)\right]}{\left[\mu_3(\lambda_3 + \mu_2)(\lambda_4 + \mu_1)\right]} \tag{6.135}$$

where

P_0, P_1, P_2, and P_3 = transit system steady-state probabilities being in states 0, 1, 2, and 3, respectively

The transit system steady state availability is given by

$$A_{ts} = P_0 \tag{6.136}$$

where

A_{ts} = transit system steady-state availability

6.12 Model XI

This mathematical model represents a transit system (e.g., a vehicle) that can either fail safely or fail with accident due to hardware failures or human errors [9–11]. The failed transit system is towed to the repair workshop for repair. After repair, the transit system is put back into operation. The system state-space diagram is shown in Figure 6.11. The numerals in boxes and circle denote system states.

The following assumptions are associated with the model:

- Transit system failure, repair, and towing rates are constant.
- Human errors and failures occur independently.
- The repaired transit system is as good as new.

The following symbols are associated with the model:

i = ith state of the transit system, where i = 0 (transit system operating normally), i = 1 (transit system failed safely due to hardware failures), i = 2 (transit system failed safely due to human errors), i = 3 (transit system failed with accident due to hardware failures), i = 4 (transit system failed with accident due to human errors), i = 5 (transit system in repair workshop)

λ_1 = transit system failing safely hardware constant failure rate

λ_2 = transit system constant safe-failure human error rate

λ_3 = transit system constant hardware failure rate that causes an accident

λ_4 = transit system constant human error rate that causes an accident

λ_5 = transit system constant towing rate from 1 to state 5

μ_w = transit system constant repair rate from state 5 to state 0

$P_i(t)$ = probability that the transit system is in state i at time t, for i = 0,1,2,3,4,5

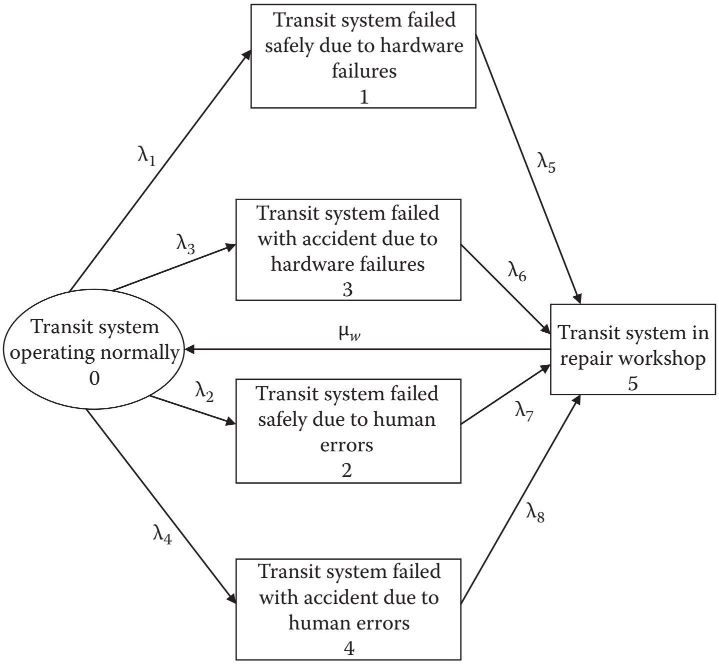

FIGURE 6.11
State space diagram for Model XI.

λ_6 = transit system constant towing rate from state 3 to state 5
λ_7 = transit system constant towing rate from state 2 to state 5
λ_8 = transit system constant towing rate from state 4 to state 5

Using the Markov method described in Chapter 4 and Figure 6.11, we write down the following equations [9–11]:

$$\frac{dP_0(t)}{dt} + (\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4)P_0(t) = \mu_w P_5(t) \tag{6.137}$$

$$\frac{dP_1(t)}{dt} + \lambda_5 P_1(t) = \lambda_1 P_0(t) \tag{6.138}$$

$$\frac{dP_2(t)}{dt} + \lambda_7 P_2(t) = \lambda_2 P_0(t) \tag{6.139}$$

$$\frac{dP_3(t)}{dt} + \lambda_6 P_3(t) = \lambda_3 P_0(t) \tag{6.140}$$

$$\frac{dP_4(t)}{dt} + \lambda_8 P_4(t) = \lambda_4 P_0(t) \tag{6.141}$$

$$\frac{dP_5(t)}{dt} + \mu_w P_5(t) = \lambda_5 P_1(t) + \lambda_7 P_2(t) + \lambda_6 P_3(t) + \lambda_8 P_4(t) \tag{6.142}$$

At time $t = 0$, $P_0(0) = 1$, $P_1(0) = 0$, $P_2(0) = 0$, $P_3(0) = 0$, $P_4(0) = 0$, and $P_5(0) = 0$.

By solving Equations (6.137)–(6.142), we get the following steady-state probability equations [9–11]:

$$P_0 = 1/(1 + L_1) \tag{6.143}$$

where

$$L_1 = \frac{\lambda_1}{\lambda_5} + \frac{\lambda_2}{\lambda_7} + \frac{\lambda_3}{\lambda_6} + \frac{\lambda_4}{\lambda_8} + \frac{L_2}{\mu_w} \tag{6.144}$$

$$L_2 = \lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 \tag{6.145}$$

$$P_1 = \frac{\lambda_1}{\lambda_5} P_0 \tag{6.146}$$

$$P_2 = \frac{\lambda_2}{\lambda_7} P_0 \tag{6.147}$$

$$P_3 = \frac{\lambda_3}{\lambda_6} P_0 \tag{6.148}$$

$$P_4 = \frac{\lambda_4}{\lambda_8} P_0 \tag{6.149}$$

$$P_5 = \frac{L_2}{\mu_w} P_0 \tag{6.150}$$

where

P_0, P_1, P_2, P_3, P_4, and P_5 = transit system steady-sate probabilities being in states 0, 1, 2, 3, 4, and 5, respectively

The transit system steady-state availability is given by

$$AV_{ss} = P_0 = \frac{1}{(1 + L_1)} \tag{6.151}$$

where

AV_{ss} = transit system steady-state availability

By setting $\mu_w = 0$ in Equations (6.137)–(6.142) and then solving the resulting equations, we get

$$R_{ts}(t) = P_0(t) = e^{-(\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4)t} \tag{6.152}$$

where

$R_{ts}(t)$ = transit system reliability at time t

The transit system mean time to failure is given by [5]

$$MTTF_{ts} = \int_0^\infty R_{ts}(t)dt$$

$$= \int_0^\infty e^{-(\lambda_1+\lambda_2+\lambda_3+\lambda_4)t}dt$$

$$= \frac{1}{(\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4)} \tag{6.153}$$

where

$\mathrm{MTTF}_{\mathrm{ts}}$ = transit system mean time to failure

Example 6.8

Assume that in Figure 6.11 we have the following given values for transition rates:

$$\lambda_1 = 0.0001 \mathit{failures/hour}$$

$$\lambda_2 = 0.0002 \mathit{errors/hour}$$

$$\lambda_3 = 0.0003 \mathit{failures/hour}$$

$$\lambda_4 = 0.0004 \mathit{errors/hour}$$

$$\lambda_5 = 0.0005/\mathit{hour}$$

$$\lambda_6 = 0.0006/\mathit{hour}$$

$$\lambda_7 = 0.0007/\mathit{hour}$$

$$\lambda_8 = 0.0008/\mathit{hour}$$

$$\mu_w = 0.0009 \mathit{reapirs/hour}$$

Calculate the transit system steady-state availability.

By substituting the specified data values into Equations (6.143)–(6.145), we get

$$Av_{ss} = P_0 = \frac{1}{1+2.5968} = 0.2780$$

$$L_1 = \frac{(0.0001)}{(0.0005)} + \frac{(0.0002)}{(0.0007)} + \frac{(0.0003)}{(0.0006)} + \frac{(0.0004)}{(0.0008)} + \frac{(0.001)}{(0.0009)}$$

$$= 2.5968$$

$$L_2 = (0.0001+0.0002+0.0003+0.0004)$$
$$= 0.001$$

Thus, the transit system steady-state availability is 0.2780.

Problems

1. Assume that a three-state transit system, whose state-space diagram is shown in Figure 6.1, has a constant failure rate of 0.0007 failures per hour. Calculate the transit system reliability during a 6-hour mission and mean time to failure.
2. Prove Equations (6.29)–(6.32) by using Equations (6.25)–(6.28).
3. Assume that in Figure 6.2 we have the following data values:

   $$\lambda_1 = 0.0003 \, failures/hour$$

   $$\lambda_2 = 0.0005 \, failures/hour$$

   $$\lambda_3 = 0.0001 \, failures/hour$$

   $$\lambda_4 = 0.0002 \, failures/hour$$

   Calculate the vehicle/transit system mean time to failure.
4. Prove that the sum of Equations (6.62), (6.63), (6.64), and (6.65) is equal to unity.
5. Assume that a vehicle fail-safe and fail with accident constant failure rates are 0.0009 failures/hour and 0.0002 failures/hour, respectively. Calculate the vehicle reliability during a 10-hour mission and mean time to failure.
6. Obtain Equations (6.40)–(6.44) by using Equations (6.36)–(6.39).
7. Compare Model V with Model VI.
8. Assume that in Equation (6.57), we have the following given data values:

   $$\alpha = 0.0004 \, transitions/hour$$

   $$\beta = 0.0002 \, transitions/hour$$

   $$\lambda_n = 0.0006 \, failures/hour$$

   $$\lambda_s = 0.0003 \, failures/hour$$

   Calculate the vehicle mean time to failure.
9. Compare Model VI with Model VII.
10. Obtain Equations (6.116)–(6.122) by using Equations (6.112)–(6.115).

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7

Rail Safety

7.1 Introduction

Rail is an important mode of transportation throughout the world. Each year, billions of dollars worth of goods and millions of passengers are transported from one point to another through railroads.

Over the years, railway safety has been an important issue. In the United States, the Congress passed the Federal Railway Safety Appliances Act in 1893. The act instituted mandatory requirements for automatic couplers and air brake systems, and standardization of the locations and specifications for appliances. Over the years, due to actions such as this, the rail safety in the United States has improved quite dramatically.

For example, according to FRA 2000, a Federal Rail Administration (FRA) report, the period 1993–1999 was the safest in U.S. rail history [1]. More specifically, during this period, train-accident-related fatalities dropped by 87%, rail worker casualties fell by approximately 34%, and highway/rail grade crossing-related fatalities decreased by more than 35% [1]. The rail industry's $50+-billion investment in infrastructure and equipment over the preceding decade is considered to be an important factor in reducing rail accidents.

This chapter presents various important aspects of rail safety.

7.2 Causes of Railway-Related Accidents and Incidents, and Examples of the Causes of Specific Rail Accidents

Over the years, there have been many different causes for the occurrence of railway-related accidents and incidents around the world. A study of 666 railway-related accidents and incidents in Sweden during the period 1888–2000 grouped the causes for their occurrence under the following three categories (along with their corresponding occurrence percentages in parentheses) [2]:

- **Rolling stock (47%)**. The causes under this category are associated with track-bound vehicles such as trains and trolleys and include operator and maintenance errors.
- **Rail and track (39%).** The causes under this category are caused by or along the railway line, including the ballast, sleepers, switches, and objects placed on or close to the track. The category also includes work on the track (e.g., maintenance and shunter actions).
- **Insufficient information (14%).** Accidents and incidents under this category had insufficient information on the causes of accidents and incidents.

The study grouped the causes of the 256 rail- and track-related accidents under the following four classifications (along with their corresponding occurrence percentages in parentheses) [2]:

- Maintenance (30%)
- Railway operation (30%)
- Sabotage (27%)
- Uncertain (13%)

The maintenance-related classification was further divided into two groups (along with the corresponding occurrence percentage in parentheses): maintenance execution (24%), lack of maintenance (6%).

Some examples of the causes of some specific rail accidents are as follows:

- A passenger train derailed due to excess speed on poor track in Ballinasloe, Ireland, on October 29, 1864, and resulted in 2 fatalities and 34 injuries [3].
- A passenger train left the station without train staff and collided head-on with a freight train in Donegal, Ireland, on August 29, 1949, and resulted in three fatalities and an unknown number of injuries [3].
- A northbound Main South Line express freight train collided with a stationary southbound freight train due to misunderstanding of track warrant conditions by both train drivers in Waipahi, New Zealand, on October 20, 1999, and resulted in one fatality and one serious injury [4].
- A Cromwell to Dunedin passenger train derailed on a curve due to excessive speed because of an intoxicated driver in Hyde, New Zealand, on June 4, 1943, and resulted in 21 fatalities and 47 injuries [4].
- A Wellington to Auckland express train rear-ended a northbound freight train after it passed a faulty semaphore signal that incorrectly

displayed clear instead of danger in Whangamarino, New Zealand, on May 27, 1914, and resulted in three fatalities and five serious injuries [5].

- A passenger train, delayed by a cow on the line, was struck from behind by another passenger train mistakenly signalled into section in Dundrum, Ireland, on December 23, 1957, and resulted in one fatality and four injuries [6, 7].
- A train derailed from a bridge damaged by road vehicles near Gorey, Ireland, on December 31, 1975, and resulted in 5 fatalities and 30 injuries [8].
- An Amtrak Auto-train derailed due to malfunctioning brakes and poor track maintenance near Crescent City, Florida, United States, on April 18, 2002, and resulted in 4 fatalities and 142 injuries [9].
- A Union Pacific Railroad train failed to stop at a signal and collided with another train in Macdona, Texas, United States, on June 28, 2004, and resulted in 3 fatalities and 51 injuries [10].

7.3 General Classifications of Rail Accidents by Effects and Causes

Over the years, various general classifications of rail accidents according to effects and causes have been proposed. The commonly proposed general classifications of the rail accidents by effects are as follows [11–13]:

- **Collisions.** These include head-on collisions, rear collisions, collisions with buffer stops, and obstructions on the line/track (i.e., road vehicles, landslides, avalanches, etc.).
- **Derailments.** These include plain track, curves, and junctions.
- **Other.** This category includes items such as fires and explosions (including sabotage/terrorism), falls from trains, and collisions with people on tracks.

The common general classifications of rail accidents by causes are as follows [11–13]:

- **Drivers' errors.** These include errors such as passing signals at danger, excessive speed, and engine mishandling.
- **Signalmen's errors.** These include errors such as allowing two trains into the same occupied block section and incorrect operation of signals, points, or token equipment.

- **Mechanical failure of rolling stock** (because of poor design and maintenance).
- **Civil engineering failure.** This classification includes bridge and tunnel collapses and track (permanent way) faults.
- **Acts of other people.** This classification includes the acts of other railway personnel (e.g., shunters, porters) and of nonrailway personnel (i.e., accidental damage, vandalism, and terrorism).
- **Contributory factors.** This classification includes factors such as rolling stock strength, effectiveness of brakes, poor track or junction layout, and inadequate rules.

7.4 Rail Derailment Accidents and Incidents and Their Causes

Over the years, there have been many rail derailment accidents and incidents around the world, in which many fatalities and injuries have occurred. Some examples of such accidents/incidents are presented below [14].

- A Camden and Amboy train derailed in Hightstown, New Jersey, United States, on November 11, 1833, and resulted in 2 fatalities and 15 injuries.
- A military train derailed in Saint Michel de Maurienne, France, on December 12, 1917, and resulted in over 500 fatalities. Up to the end of the 20th century, this disaster was considered the world's worst-ever derailment.
- A Pennsylvania Railroad express passenger train derailed near Altoona, Pennsylvania, United States, on February 18, 1947, and resulted in 24 fatalities and 131 injuries.
- A train from Beijing, China, to Qingdao, China, derailed in Shandong, China, on April 28, 2008, and resulted in 70 fatalities and 400 injuries.

There are many causes of rail derailment accidents and incidents. Some of the main ones are as follows [14]:

- **Rail breakages.** These include rail breaks at rail joints, manufacturing-defect-related rail breaks, wheelburn-related rail breaks, and cold-weather-related rail breaks.
- **Misaligned railroad tracks.** There are various types of misaligned plain line tracks that can cause or contribute to a derailment,

including wide-to-gauge, wrong cross level, incorrect alignment, wash out, and incorrect cant/super elevation.

- **Excessive speed.** There are two different mechanisms that cause excessive-speed derailments: wheel climb and rail roll. In the case of wheel climb, the wheel is lifted off the track because the friction between the flange and the gauge face of the rail is too high. Consequently, it causes the wheel flange to climb outwards over the head of the rail. Similarly, in the case of rail roll, the flange horizontal force applied to the gauge face of the rail is too high, overcoming the anchoring forces of rail clips and spikes.
- **In-train forces.** These occur due to factors such as uneven loading, poor train-handling techniques, and train "stringlining" on sharp reverse curves.
- **Wheel and truck failures.** Some of the main reasons for wheel and truck failures are hot axle box, fracture of axle, and fracture of wheel.

7.5 Telescoping-Related Railway Accidents

In rail accidents, telescoping occurs when the under frame of one vehicle overrides that of another vehicle, and smashes through the body of the second vehicle. The term "telescoping" is derived from the resulting appearance of the bodies of both vehicles. More specifically, the body of one vehicle may appear to be slid inside the body of the other vehicle like the tubes of a collapsible telescope (i.e., roof, under frame, and the body sides of the latter vehicle being forced apart from each other).

Past experiences indicate that telescoping often resulted in heavy fatalities when the telescoped train cars were fully occupied. The occurrence of telescoping-related accidents can be reduced quite significantly with the use of anticlimbers and crash-energy-management structural systems.

Two important examples of rail telescoping-related accidents are the Chicago commuter rail crash and the Seer Green rail crash in the United Kingdom. The Chicago commuter rail crash, considered to be the worst in Chicago's history, occurred on October 30, 1972, when Illinois Central Gulf Train 416 overshot the 27th Street Station and collided with an express train. When the trains collided, the front car of the express train telescoped the rear car of the Illinois Central Gulf Train 416 [15]. The accident resulted in 45 fatalities and 332 injuries. Additional information on the accident is available in a report by the National Transportation Safety Board [15].

The Seer Green rail crash occurred on December 11, 1981, near Seer Green, Buckinghamshire, United Kingdom, when the driver of a train carrying passengers drove too fast for the surrounding conditions and ran into the back of an empty train at about 30 miles per hour [16]. The front coach of the train carrying passengers partly telescoped underneath the rear coach of the empty train. The accident caused 4 fatalities and 5 injuries. Additional information on the accident is available in a report by Rose [16].

7.6 Railway Accidents in Selected Countries

Ever since the use of the steam engine for rail transportation, a vast number of accidents, with fatalities, have occurred throughout the world [17]. Railway accidents in four selected countries are presented in the following subsections.

7.6.1 United Kingdom

Ever since the development of the steam engine by James Watt, there have been many railway accidents with fatalities in the United Kingdom. The first railway passenger fatality occurred on September 15, 1830, when William Huskisson was killed at the opening of the Liverpool and Manchester Railway line. A railway accident that occurred on May 22, 1915, at Quintinshill was probably the worst rail accident in the United Kingdom with respect to fatalities [17]. The accident caused 227 fatalities and 246 injuries.

The approximate breakdowns of railway-related fatalities versus number of accidents occurring during the period 1830–2007 in the United Kingdom are presented in Table 7.1 [17].

7.6.2 Ireland

Since 1853, there have been many fatal railway accidents in Ireland. In fact, during the period 1853–1983, there were around 37 fatal rail accidents [3]. The

TABLE 7.1

Approximate Breakdowns of Fatalities versus Number of Railway Accidents in the United Kingdom, 1830–2007

Fatality Range or No. of Fatalities	No. of Accidents
>50	5
10–50	76
6–9	23
5	11
4	7
3	4
2	7
1	15

Source: [17].

TABLE 7.2
Railway Accidents that Caused Five or More Fatalities in Ireland, 1853–1980

Accident No.	Accident Date	Accident Location	No. of Fatalities	No. of Injuries
1	August 1, 1980	Buttevant, County Cork	18	75
2	October 5, 1853	Straffan, County Kildare	16	8
3	August 21, 1983	Cherryville Junction, County Kildare	7	55
4	November 19, 1856	Dunkettle, near County Cork	6	…
5	December 19, 1916	Kiltimagh, County Mayo	6	10
6	December 31, 1975	Near Gorey, County Wexford	5	30
7	September 8, 1878	Curraheen, County Cork	5	70

Source: [3].

first fatal railway accident occurred on October 5, 1853, at Straffan, County Kildare, Ireland, and it caused 16 fatalities and 8 injuries.

The railway accidents that caused five or more fatalities are presented in Table 7.2 [3].

7.6.3 New Zealand

Since 1880, there have been many railway accidents in New Zealand. In fact, during the period 1880–2009, there were around 30 fatal/nonfatal rail accidents [5, 18]. The first reported fatal railway accident occurred on September 11, 1880, at the Rimutaka Incline, Wellington, and it resulted in 3 fatalities and 11 injuries. The worst railway accident in the country occurred on December 24, 1953, at Tangiwai, which caused 151 fatalities [5].

The breakdowns of railway accidents occurring during the period 1880–2009 in New Zealand, are presented in Table 7.3 [5, 18].

7.6.4 Australia

Over the years, there have been many rail accidents in Australia. During the period 1857–2007, there were around 41 major railway accidents. Australia's first fatal accident occurred on June 25, 1857, when a railway worker fell from a locomotive as it passed under a bridge [19, 20].

The worst railway accident in Australia, with respect to fatalities, occurred on January 18, 1977, at Granville, New South Wales, when a packed peak-hour train derailed and crashed into a concrete bridge and caused 83 fatalities. The breakdowns of major railway accidents occurring during the period 1857–2007 in Australia are presented in Table 7.4 [19, 20].

TABLE 7.3

Breakdown of New Zealand's Major Railway Accidents, 1880–2009

Time Period	No. of Accidents
2000–2009	2
1950–1999	17
1900–1949	9
1880–1899	2

Source: [5, 18].

TABLE 7.4

Breakdown of Australia's Major Railway Accidents, 1857–2007

Time Period	No. of Accidents
2000–2007	3
1950–1999	14
1900–1949	16
1857–1899	8

Source: [19, 20].

7.7 Railroad Tank Car Safety

Railroad tank cars are used to transport liquids and gases from one point to another. Currently, there are about 115,000 railroad tank cars operating in the United States alone. The contents of these tank cars are flammable, corrosive, poisonous, or pose other hazards if released accidently. During the period 1965–1980, more than 40 people were killed in tank car accidents in the United States [21]. Furthermore, accidental releases occur approximately once out of every 1,000 shipments, resulting in around 1,000 releases per year.

To ensure tank car safety, the United States Department of Transportation and the industrial sector have taken various steps to enhance both the tank car and the environment in which it functions. In the 1990 Hazardous Materials Transportation Uniform Safety Act, the U.S. Congress called for the followings [21]:

- An examination of the tank car design process
- An assessment of whether head shields should be made mandatory on all railroad tank cars that carry hazardous materials

In order to address these two issues, the Transportation Research Board (TRB) formed a committee whose members had expertise in tank car design, railroad operations and labor, transportation economics and regulation, transportation and hazardous materials safety, chemical and mechanical engineering, and chemical shipping. After a careful examination of railroad tank car incident data, the committee recommended the following measures [21]:

- Enhance the implementation of industry design approval and certification function and federal oversight procedures and processes.
- Improve the information and criteria employed to assess the safety performance of tank car design types and to assign materials to tank cars.
- Enhance cooperation between industry and the Department of Transportation to identify critical safety needs and take action for achieving them.

7.8 Light-Rail Transit-System Safety-Related Issues

Light-rail transit systems are being used in about 20 cities in the United States and Canada. Some of the main reasons for their usage are their relatively low costs and ability to operate both on and off city streets, with intermediate capacity to transport passengers and with frequent stops in urban areas.

Over the years, there have been many light-rail transit-system-related accidents resulting in fatalities and injuries. For example, in the three-year period from the opening of the Metro Blue Line (MBL) in Los Angeles, there were 158 train–vehicle and 24 train–pedestrian accidents/incidents resulting in 16 deaths and many injuries [22].

Nonetheless, some of the safety problems and areas of concern (i.e., safety issues) related to light-rail transit operations on city streets as well as on reserved rights of way with at-grade crossings are as follows [22]:

- Crossing equipment failure
- Motorist disobedience with respect to traffic laws
- Light-rail vehicles blocking street/road and pedestrian crosswalk areas at crossing points
- Vehicles turning from streets or roads that run parallel to the rail tracks
- Road vehicles making left or U-turns in front of rail vehicles or stopping on rail tracks
- Traffic queues blocking crossing points
- Motorist confusion over light-rail transit signals, traffic signals, and signage at intersection points
- Pedestrian conflicts at station areas and crossing points

7.9 Methods for Performing Rail Safety Analysis

There are numerous methods and techniques developed in areas such as safety, reliability, and quality for conducting various types of analysis [23–25]. Some of these methods and techniques can also be used to perform rail safety analysis. These methods and techniques include fault-tree analysis, hazards and operability analysis, cause-and-effect diagram, interface safety analysis, failure modes and effect analysis, and Pareto diagram. One of these approaches (i.e., fault-tree analysis) is presented below, and information on other methods and techniques is available in Chapter 4 and in the literature [23–25].

7.9.1 Fault-Tree Analysis

This is a widely used method to perform safety and reliability analysis of engineering systems in industry. The method was developed in the early 1960s at the Bell Telephone Laboratories to perform safety analysis of the Minuteman launch control system, and it is described in Chapter 4 [24].

In order to demonstrate the application of fault-tree analysis in the area of rail safety, using the fault-tree symbols defined in Chapter 4, a simple fault tree for the top event—release of liquefied chlorine from a rail tank shell—is shown in Figure 7.1 [25]. The capital letters in the circles and rectangles of the fault-tree diagram in Figure 7.1 denote, respectively, basic and intermediate fault events associated with the rail tank shell. Each of these capital letters is defined below [25].

- A: Release from tank head
- B: Release from tank wall
- C: Release from midway cover
- D: Tank shell fails due to end impact
- E: Fire-related forces fail tank head
- F: Crush load fails tank head
- G: Puncture probe fails tank head
- H: Accident occurs
- I: Puncture load sufficient to fail tank head
- J: Puncture strikes tank head

Example 7.1

Assume that the probabilities of occurrence of independent events B, C, D, E, F, H, I, and J in Figure 7.1 are .08, .07, .06, .05, .04, .03, .02, and .01, respectively.

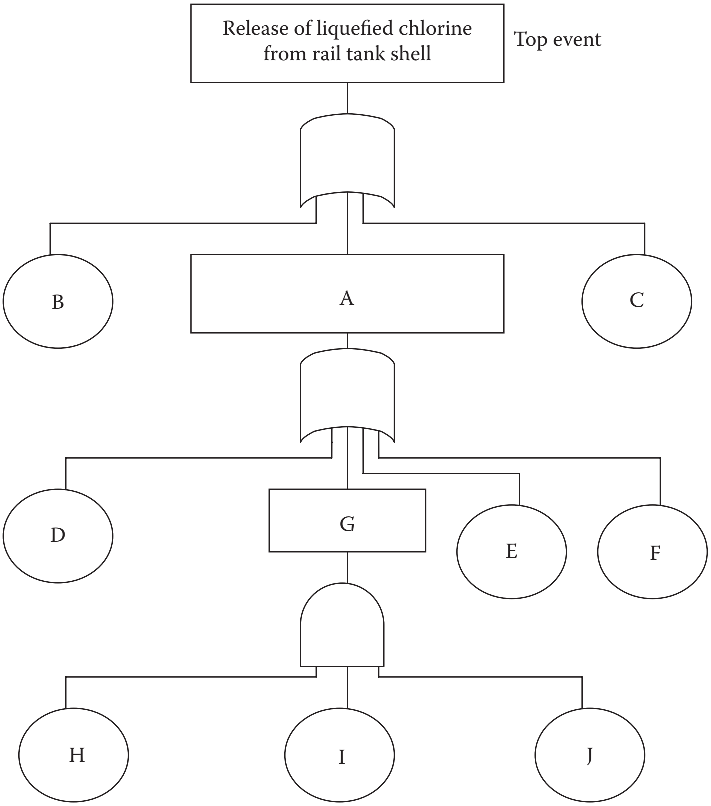

FIGURE 7.1
A fault tree for the top event: Release of liquefied chlorine from rail tank shell.

Calculate the probability of occurrence of the top event—release of liquefied chlorine from rail tank shell—by using equations presented in Chapter 4.

Thus, from Chapter 4, the probability of occurrence of event G is

$$P(\mathrm{G}) = P(\mathrm{H})\ P(\mathrm{I})\ P(\mathrm{J}) \tag{7.1}$$

where

$P(\mathrm{H})$ = probability of occurrence of event H
$P(\mathrm{I})$ = probability of occurrence of event I
$P(\mathrm{J})$ = probability of occurrence of event J

For the given values of $P(\mathrm{H})$, $P(\mathrm{I})$, and $P(\mathrm{J})$, from Equation (7.1) we get

$$P(\mathrm{G}) = (.03)(.02)(.01)$$
$$= .000006$$

Similarly, from Chapter 4, the probability of occurrence of event A is

$$P(\mathrm{A}) = 1 - [1 - P(\mathrm{D})]\ [1 - P(\mathrm{G})]\ [1 - P(\mathrm{E})]\ [1 - P(\mathrm{F})] \tag{7.2}$$

where

$P(\mathrm{D})$ = probability of occurrence of event D
$P(\mathrm{G})$ = probability of occurrence of event G
$P(\mathrm{E})$ = probability of occurrence of event E
$P(\mathrm{F})$ = probability of occurrence of event F

For the above calculated and given values of $P(\mathrm{D})$, $P(\mathrm{G})$, $P(\mathrm{E})$, and $P(\mathrm{F})$, Equation (7.2) yields

$$\begin{aligned} P(\mathrm{A}) &= 1 - [1 - .06]\,[1 - .000006]\,[1 - .05]\,[1 - .04] \\ &= .1427 \end{aligned}$$

Finally, the probability of occurrence of the top event, release of liquefied chlorine from rail tank shell, is expressed by

$$P(\mathrm{T}) = 1 - [1 - P(\mathrm{B})]\,[1 - P(\mathrm{A})]\,[1 - P(\mathrm{C})] \tag{7.3}$$

where

$P(\mathrm{T})$ = probability of occurrence of the top event T, release of liquefied chlorine from rail tank shell
$P(\mathrm{B})$ = probability of occurrence of event B
$P(\mathrm{C})$ = probability of occurrence of event C

For the above calculated and given values of $P(\mathrm{A})$, $P(\mathrm{B})$, and $P(\mathrm{C})$, from Equation (7.3), we get

$$\begin{aligned} P(\mathrm{T}) &= 1 - [1 - .08]\,[1 - .1427]\,[1 - .07] \\ &= .2665 \end{aligned}$$

Thus, the probability of occurrence of the top event, release of liquefied chlorine from rail tank shell, is .2665. The fault tree of Figure 7.1, with the given and the above calculated event-occurrence probability values, is shown in Figure 7.2.

Problems

1. Write an essay on rail safety.
2. Give at least five examples of the causes of some specific rail accidents.
3. What are the common general classifications of rail accidents by causes?
4. Discuss general classifications of rail accidents by effects.
5. Give at least three examples of rail derailment accidents/incidents.
6. What are the main causes of rail derailment accidents and incidents?
7. Discuss telescoping-related rail accidents.
8. Discuss railway accidents in the following four countries:
   a. United Kingdom
   b. Ireland
   c. Australia
   d. New Zealand
9. Discuss railroad tank car safety.
10. List at least eight light-rail transit system safety-related issues.

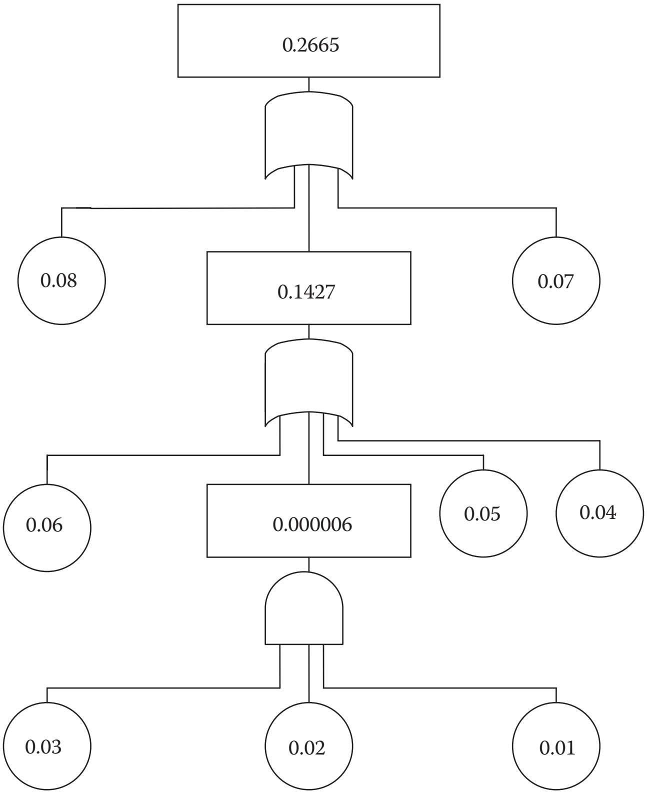

FIGURE 7.2
Redrawn Fig. 7.1 fault tree with the given and calculated event occurrence probability values.

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8

Truck and Bus Safety

8.1 Introduction

Commercial truck and bus transport have major economic importance in most of the developed countries. For example, in the United States, the commercial trucking sector alone employs around 10 million people, and its annual revenue is greater than $500 billion [1]. Furthermore, intercity and charter buses in North America carry around 860 million passengers per year, more than are transported by either rail or commercial air carriers [1].

In 2003, there were a total of 42,643 traffic crash fatalities in the United States, out of which 4,986 involved large trucks. The economic impact of crashes involving large trucks and buses is quite significant. For example, according to Zaloshnja and Miller [2], in 2000, the average cost of crashes involving large trucks (i.e., greater than 10,000 lbs.) was $59,153, and the average cost of crashes involving transit or intercity buses was $32,548. All in all, during the period 1997–1999, the total annual costs of large truck crashes and bus crashes in the United States were $19.6 billion and $0.7 billion, respectively [1].

This chapter presents various important aspects of truck and bus safety.

8.2 Top Truck and Bus Safety Issues

Over the years, various studies have identified many truck and bus safety-related issues. Some of the top ones are as follows [3]:

- **Fatigue.** This is concerned with driving, unloading, scheduling, and road conditions that induce fatigue, in addition to hours-of-service violations and a lack of proper places to rest.
- **Data/Information.** This is concerned with the shortage of information concerning heavy vehicle crashes and their associated causes.
- **Technology.** This is concerned with the development and deployment of emerging and practically inclined technologies for improving safety.

- **Driver training.** This is concerned with the need for better and continuing education for all drivers (i.e., commercial and private).
- **Uniform regulations.** This is concerned with the lack of uniformity in safety regulations and procedures among U.S. states and between Canada and Mexico, indicating that safety issues do not receive the same priority in all jurisdictions.
- **Enforcement.** This is concerned with the need for more effective testing and licensing, traffic enforcement, and adjudication of highway user violations.
- **Working conditions.** This is concerned with the review of standards and industry practices as they affect driver workload.
- **License deficiencies.** This is concerned with the review of testing procedures for commercial driver's licenses.
- **Communications.** This is concerned with the development of a national motor-carrier safety marketing campaign and the expansion of education efforts to the public for sharing roads with large vehicles.
- **Resource allocations.** This is concerned with the priorities and allocation of scarce resources through better safety-management systems that give safety the top priority.
- **Partnership.** This is concerned with better communication and coordination among highway users.
- **Accident countermeasures.** This is concerned with the research efforts targeted to seek and define proactive and nonpunitive countermeasures for preventing the occurrence of accidents.

8.3 Truck Safety–Related Facts and Figures

Some facts and figures that are concerned, directly or indirectly, with truck safety are as follows:

- Large trucks account for around 3% of all registered vehicles in the United States, and each truck on the average travels about 26,000 miles per year [4].
- In 1993, approximately 4,500 trucks in the United States were involved in an accident in which at least one fatality occurred [4].
- As per the Insurance Institute for Highway Safety about 65% of large truck crash deaths occur on major roads in the United States [4].
- In 1993, according to the Federal Highway Administration's Office of Motor Carriers (OMC), about 80% of all truck accidents in the United States occurred with no adverse weather conditions [4].

- During the period 1976–1987, fatalities of truck occupants in the United States decreased from 1,130 in 1976 to 852 in 1987 [5].
- During the period 1993–2003, the fatal crash rate for large trucks in the United States declined by 20% [1].
- In 2003, out of 4,986 fatalities that occurred from crashes involving large trucks in the United States, 14% were occupants of large trucks, 78% were occupants of another vehicle, and 8% were nonoccupants [1, 6].
- According to the Centers for Disease Control (CDC), commercial drivers in the United States experience more job-related deaths than any other profession [1, 7].
- In the United States, there were approximately 5,400, 5,100, 5,000, 4,000, 4,500, 4,900, and 5,000 truck-related fatal crashes in 1980, 1986, 1989, 1992, 1995, 1997, and 2000, respectively [1].

8.4 Commonly Cited Truck Safety–Related Problems, Factors Associated with Heavy-Vehicle Accidents, and Safety Culture in the Trucking Industry

The most commonly cited truck safety–related problems are as follows [4]:

- **Angle impact.** This accounts for around 32.5% of fatal truck involvements, 37.1% of injury involvements, and 37.7% of tow-away involvements.
- **Head-on collisions.** These account for around 24% of fatal truck involvements, 1.6% of injury involvements, and 1.9% of tow-away involvements.
- **Rear-end collisions.** These account for around 18.4% of fatal truck involvements, 30.6% of injury involvements, and 26.9% of tow-away involvements.
- **Sideswipes.** These account for around 4.1% of fatal truck involvements and 9.7% of tow-away involvements.
- **Rollovers.** These account for around 13.3% of fatal truck involvements, 10.8% of injury involvements, and 8.6% of tow-away involvements.
- **Jackknifes.** These occur when a multi-unit vehicle (e.g., tractor-trailer) folds up like a pocket knife. Jackknifes account for around 8.3% of fatal truck involvements, 5.5% of injury involvements, and 8.4% of tow-away involvements.

The three most frequently associated factors with heavy-vehicle accidents are shown in Figure 8.1 [5]. Additional information on these three factors is available in Seiff [5].

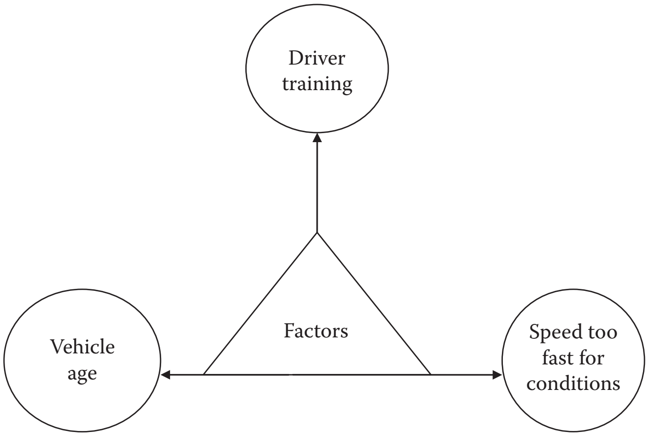

FIGURE 8.1
Most frequently associated factors with heavy vehicle accidents.

Over the years, in many industrial settings, it has been recognized that the existence of a strong safety culture has a positive impact on safety outcomes such as accident frequency and severity [8–10]. The main factors that can affect safety culture in the trucking industry include driver safety training, driver scheduling autonomy, driver opportunities for safety input, and top management commitment to safety [11]. Careful consideration to such factors can significantly improve the safety culture in the trucking industry, with a positive outcome on safety. Additional information on the safety culture in the trucking industry is available in Arboleda et al. [11].

8.5 Safety-Related Truck Inspection Tips, Safety-Related Tips for Truck Drivers, and Recommendations for Improving Truck Safety

Over the years, past experience has indicated that most truck-associated incidents result from mechanical failures, faulty brakes and tires, cracked suspensions, and electrical failures [4]. Detection is considered the best approach for avoiding the occurrence of such incidents. This can easily be accomplished with a daily "walk around" by drivers and through a regular preventive maintenance program. For example, during a trip, drivers should watch gauges for signs of trouble and use their senses (look, listen, smell, feel) to check for problems. Furthermore, whenever the truck is parked, the driver should check critical items such as brakes, tires, wheels and rims, lights and reflectors, and electrical connections to the trailer [4]. Some of the basic safety-related tips for truck drivers are shown in Figure 8.2 [4].

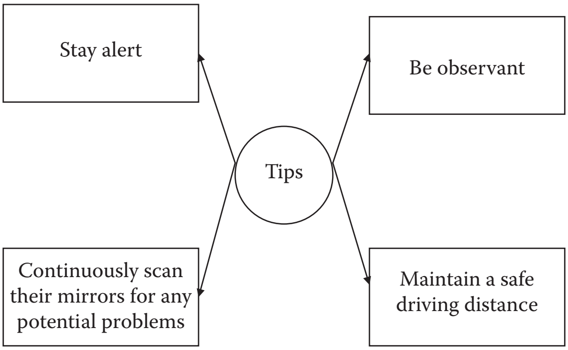

FIGURE 8.2
Basic safety-related tips for truck drivers.

The attendees of a conference (Truck Safety: Perceptions and Reality) in 1995 made many recommendations on the following five issues for improving truck safety [8]:

- Driver training and empowerment
- Driver fatigue
- Vehicle brakes and maintenance standards
- Harmonization of safety standards across all jurisdictions
- Data needs

The recommendations on the driver training and empowerment issue were as follows [12]:

- Develop effective driver training and retraining programs that specifically focus on safety (e.g., teaching drivers to inspect the vehicle with the aid of the latest technology) and to take appropriate measures to reduce all types of accident risk.
- Aim to implement a graduated licensing scheme that clearly reflects the needs of different types of trucking vehicles.
- Aim to enact a thorough accreditation of all driver training schools to ensure that they uniformly satisfy desired standards in all jurisdictions in question.
- Aim to devise and enforce regulations to ensure that truck-drivers are not unfairly dismissed for their refusal to drive in unsafe conditions.

The recommendations on the driver-fatigue issue were as follows [12]:

- Develop a comprehensive approach to identify the incidence of truck drivers' fatigue that takes into consideration different types of fatigue and driving needs.

- Aim to harmonize all appropriate standards across different jurisdictions.
- Develop appropriate tolerance levels for accident risk and fatigue, and devise new standards that clearly incorporate these levels.

The recommendations on the issues of vehicle brakes and maintenance standards were as follows [12]:

- Aim to train and certify all truck drivers to adjust vehicle brakes appropriately as part of their ongoing training program and licensing requirements.
- Equip all trucks with appropriate on-board devices/signals to indicate when brakes require adjustment and servicing.
- Implement an appropriate safety rating system.
- Invoke appropriate penalties for those trucking companies that regularly fail to satisfy necessary inspection standards.

The recommendations on the harmonization issue were as follows [12]:

- Establish an agency for gathering and disseminating safety-related information to all concerned parties.
- Form a committee of government and industry representatives to explore appropriate avenues for cooperative efforts in developing uniform safety-related standards for trucks.

Finally, the recommendations on the data issue were as follows [12]:

- Highlight and share currently available data related to truck accidents and exposures.
- Aim to standardize police accident reporting forms in all concerned jurisdictions.
- Improve police accident report reliability through better police training for collecting and reporting reliable data on accident causes and consequences.
- Establish an appropriate North American Truck Safety data center.

8.6 Bus and Coach Occupant Fatalities and Serious Injuries

Buses and coaches are widely used to transport passengers from one point to another around the world. Each year, many passengers are killed and seriously injured in bus- and coach-related accidents. For example, in the United Kingdom, bus and coach occupant fatalities in 1966, 1970, 1975, 1980, 1985, 1990, and 1991 were 76, 74, 115, 29, 32, 19, and 25, respectively [13]. Furthermore, bus and coach passengers killed and seriously injured in those same years were 2,161, 1,924, 1,650, 1,952, 1,036, 826, and 725, respectively [13]. Additional information on this topic is available in White and Dennis [13].

8.7 Transit Bus Safety and Key Design-Related Safety Feature Areas

Although buses are one of the safest modes of transportation, during the period 1999–2003 in the United States, an average of 40 bus occupant fatalities and 18,430 injuries occurred per year [14]. In regard to two-vehicle crashes, there were 11 bus occupant fatalities per year, while there were 162 fatalities for occupants of other vehicles per year (i.e., 102 occupants in passenger cars, 2 in large trucks, 49 in light trucks, and 9 on motorcycles) [14].

During the period 1999–2001, there were an average of 111 transit buses per year involved in fatal accidents in the United States [14, 15]. Additional information on transit bus safety is available in the literature [14, 16].

Over the years, many design-related areas to improve transit-bus safety have been identified. The key safety-related features are as follows [17]:

- Low floors, wide doors, and energy-absorbing bumpers and sidewalls.
- Interior transit-bus designs based on important considerations that feature selective padding and removal of dangerous protrusions.
- Better visibility and lighting for both passengers and driver.
- Better external designs that remove all types of potentially dangerous protrusions, footholds, and handholds.

8.8 Vehicle Safety Data Sources

There are many sources in the United States that can be used, directly or indirectly, to obtain truck and bus safety-related data. The main ones are as follows [18]:

- National Highway Traffic Safety Administration
- National Transportation Safety Board

- Federal Highway Administration
- University of Michigan Transportation Research Institute
- Insurance industry

Each of these sources is described below.

8.8.1 National Highway Traffic Safety Administration

The National Center for Statistics and Analysis of the National Highway Traffic Safety Administration (NHTSA) keeps records of various types of police-reported accidents [18]. The file of reported accidents is known as the National Accident Sampling System (NASS), and it was started in the late 1970s. An accident to be included in NASS must satisfy the following three conditions [18, 19]:

- It must be reported by police.
- It must involve a motor vehicle in transport on a traffic way.
- It must cause personal injury/property damage.

The NASS investigation team examines the accident scene and vehicle, reviews medical and driver records, and interviews all vehicle occupants. Each year, over 10,000 cases are investigated by various NASS teams. Some of the main strengths of the NASS are as follows [18]:

- National estimate of accident frequency
- Comprehensive accident investigation
- Reasonable detail on truck accident characteristics

In contrast, two main weaknesses of the NASS are the lack of detailed analysis of the causes of accidents and the small number of heavy-truck accidents in the database.

8.8.2 National Transportation Safety Board (NTSB)

The NTSB performs multimodel, on-scene investigations of transportation-related accidents. The basis for its jurisdiction for performing an investigation is the definition of a major vehicular accident for each mode, as expressed in the Code of Federal Regulations, Part 49 [18].

In the latter years of the 1980s, the NTSB embarked on an extended study of heavy-truck safety [19] that included approximately 200 accidents involving heavy trucks satisfying the following two conditions [18]:

- The accident involved a truck with gross-vehicle-weight rating greater than 10,000 lbs.

- The truck was damaged to a degree where it required towing from the accident scene.

The strengths of this NTSB study are the comprehensiveness of the accident investigation, the good detail on truck characteristics, and its exclusive focus on trucks. In contrast, its main weakness is the limited sample of accidents under investigation, which are not representative of truck crashes in general [18].

8.8.3 Federal Highway Administration

The Federal Highway Administration (FHWA) has maintained a motor-carrier accident database, known as the Motor Carrier Safety Management Information System (MCMIS), since 1973 [18]. It includes any federally regulated motor-carrier accident that meets the specified reporting criteria. Prior to 1986, the criteria demanded reporting of accidents resulting in a fatality, an injury, or property damage of $2,000 or more.

In January 1986, the value of the property damage was increased to $4,200 and to $4,400 in March 1987. Subsequently, its value increased in accordance with the Gross National Product index of inflation [18].

In comparison to any other national accident database, the FHWA database provides for more detail on truck accident characteristics. It includes information on items such as carrier identification and address, incident location, information on the cargo, characteristics of the event, contributing factors, and accident consequences.

The main strengths of the MCMIS are its exclusive truck focus and good detail on truck accident characteristics. In contrast, its main weaknesses are that it misses several portions of the truck population, concerns over the accuracy and completeness of its reports, and its dependency on carrier participation [18].

8.8.4 University of Michigan Transportation Research Institute (UMTRI)

Over the years, the UMTRI has been involved in an ongoing activity concerned with the development of a database that combines the coverage of NHTSA's fatal accident reporting system (FARS) with the coverage of FHWA's motor-carrier safety management information system (MCMIS). The process followed by the UMTRI involves the identification of all heavy-truck-related accidents in the FARS database, matching these accidents with the MCMIS accident records in which a fatality occurred, accessing corresponding police reports, and then generating a single accident record that incorporates essential information from all sources [18, 20].

Note that, as the UMTRI database analysis is restricted to accidents that involve a fatality, its results alone may not be representative of most truck accidents occurring in the United States [20]. Additional information on this topic is available in the literature [18, 20, 21].

8.8.5 Insurance Industry

U.S. insurance companies that underwrite motor carriers keep statistical and financial-related information/data on insurance claims and policies. This data is also transmitted by the participating companies to the Insurance Services Office, Inc. (ISO) [18, 22]. ISO is a nonprofit organization that provides various types of data-related services to the U.S. property/casualty insurers [18, 23]. Its statistical data permit investigation of various industry characteristics, including geographic location, vehicle age, size of claim, driver age, and vehicle weight.

This database has not been a primary source of information in conducting safety analysis. Additional information on this topic is available in the literature [18, 22].

8.9 Motor Vehicle Traffic-Related Accidents in Selected Countries

Motor vehicle traffic-related accidents (including bus and truck) are becoming an important transportation issue around the world. Table 8.1 presents data on traffic-accident-related deaths and deaths per 100,000 vehicles in selected countries for 1996 [23]. This clearly shows the importance of increasing the safety standards for trucks and buses.

TABLE 8.1

Traffic-Accident-Related Deaths and Deaths per 100,000 Vehicles in Selected Countries, 1996

No.	Country	Total Deaths	Deaths per 100,000 Vehicles
1	United States	41,907	20.8
2	Thailand	15,000	125
3	Japan	11,674	17.4
4	Germany	8,758	20.2
5	France	8,541	27.8
6	United Kingdom	3,598	12.8
7	Saudi Arabia	3,123	62.4
8	Canada	3,082	18.5
9	Australia	1,973	17.6
10	Holland	1,180	18.5
11	Austria	1,027	25.6
12	Ireland	453	40.4

Source: [23].

Problems

1. Write an essay on truck and bus safety.
2. Discuss the top ten safety-related issues for trucks and buses.
3. What are the five most-important facts and figures related to truck safety?
4. List the most-cited problems related to truck safety.
5. What are the factors most frequently associated with heavy-vehicle safety?
6. Discuss useful recommendations to improve truck safety.
7. What are the main sources for obtaining data related to vehicle safety?
8. What are the key design-related features for improving safety on transit buses?
9. Discuss the trends in fatalities and serious injuries that have occurred in the United Kingdom for bus and coach occupants, 1966–1991.
10. What are the four basic safety-related tips for truck drivers?

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9

Airline and Ship Safety

9.1 Introduction

Today, airlines and ships are an important mode of transportation around the globe. The world's 900 airlines—with a total of around 22,000 aircraft—carry over 1.6 billion passengers for business and leisure travel each year, and about 40% of world trade of goods is carried by air [1–3]. Similarly, there are about 90,000 merchant ships in the world, and they transport over 90% of the world's cargo [4, 5].

Over the years, airline and ship safety has been an important issue, and various measures have been taken for its improvement. For example, in the area of civil aviation in the United States, the Air Commerce Act was passed in 1926 [6, 7]. The act required the examination and licensing of pilots and aircraft, proper investigation of accidents, and the establishment of safety rules. Due to measures such as these, the safety in the airline area has improved quite significantly, and currently the accident rate for air travel is around one fatality per 1 million flights [1–3].

In the area of sea transportation, over the years there have been many accidents and other safety-related problems. For example, the sinking of the RMS *Titanic*, a passenger liner owned by a British shipping company, in 1912 resulted in 1,517 onboard fatalities [8]. Safety in the area of sea transportation has improved quite significantly over the years, but it is still an important issue.

This chapter presents various important aspects of airline and ship safety.

9.2 United States Airline-Related Fatalities and Accident Rate

The history of airline-related crashes in the United States may be traced back to 1926 and 1927, when there were a total of 24 fatal commercial airline crashes. In 1929, there were 51 airline crashes that killed 61 people, and this remains the worst year on record, with an accident rate of around one per 1 million

TABLE 9.1

Airline-Related Fatalities in the United States, 1983–1995

No.	Year	No. of Deaths
1	1983	8
2	1984	0
3	1985	486
4	1986	0
5	1987	212
6	1988	255
7	1989	259
8	1990	8
9	1991	40
10	1992	25
11	1993	0
12	1994	228
13	1995	152

Source: [7].

miles flown [7, 9]. Airline safety in the United States has improved quite dramatically over the years, but many airline-associated fatalities still occur.

Table 9.1 presents the number of fatalities due to commercial airplane accidents in the United States for the period 1983–1995 [7]. Accident rates per 1 million flight departures for 1989, 1990, 1991, 1992, 1993, 1994, and 1995 were 0.37, 0.29, 0.33, 0.22, 0.28, 0.27, and 0.40, respectively [7].

In comparison to fatalities in other sectors, the airline fatalities are extremely low. For example, in 1995 people were about 300 times more likely to die in a motor-vehicle-related accident and about 30 times more likely to get drowned than to get killed in an airplane accident [7].

9.3 Aircraft Accidents during Flight Phases and Causes of Airplane Crashes

A flight phase may be divided into nine distinct subphases: ramp/taxi, takeoff, initial climb, climb, cruise, descent, initial approach, final approach, and landing [10]. Past experience indicates that the occurrence of accidents can vary quite considerably from one flight subphase to another. For example, during the period 1987–1996, the lowest percentage of aircraft accidents occurred during the ramp/taxi subphase and the highest during the final-approach subphase [10, 11].

More specifically, the rough breakdowns of the percentages of accidents during 1987–1996 for the subphases were: 1% (ramp/taxi), 5% (cruise), 7% (descent), 8% (climb), 10% (initial climb), 11% (initial approach), 14% (takeoff), 21% (landing), and 23% (final approach) [10, 11]. Accident data for the period 1990–1999 exhibit a similar trend [10, 12].

Past experience indicates that there are many causes of airplane crashes. For example, a study of 19 major crashes (defined as one in which at least 10% of the airplane passengers are killed) of U.S. domestic jets occurring during the period 1975–1994 has identified eight different causes of these crashes [7, 13]. These causes (with corresponding number of crashes in parentheses) were as follows [7, 13]:

- Thunderstorm wind shear (4)
- Ice buildup (3)
- Ground or air collisions (3)
- Hydraulic failure (2)
- Engine loss (2)
- Taking off without the flaps in the right position (2)
- Sabotage (1)
- Cause unknown (2)

9.4 Worldwide Airline Accident Analysis

Airlines are a widely used mode of transportation throughout the world. Currently, over 16,000 jet aircraft are being used around the world, with over 17 million departures per year [6]. A study of worldwide scheduled commercial jet operations during the period 1959–2001 indicates that there were a total of 1,307 accidents, resulting in 24,700 onboard fatalities [6, 14]. By type of operation, these 1307 accidents can be classified as follows [6]:

- Passenger operations: 1,033 accidents (79%)
- Cargo operations: 169 accidents (13%)
- Testing, training, demonstration, or ferrying: 105 accidents (8%)

The collective U.S. and Canadian component of these 1,307 accidents was around 34% (i.e., 445 accidents), which contributed about 25% (6,077) of the worldwide 24,700 onboard fatalities [6]. A study of the 1959–2001 accident data indicates that the world commercial jet fleet accident rate (i.e., accidents per million departures) has been fairly stable for the period 1974–2001 [14]. Additional information on the subject is available in the literature [6, 14].

9.5 Air Safety–Related Regulatory Bodies and Their Responsibilities

There are two bodies in the United States—the Federal Aviation Administration (FAA) and the National Transportation Safety Board (NTSB)—that serve as the public's watchdog for safety in the aviation industry. The history of both these agencies may be traced back to 1940, when the Civil Aeronautics Authority was split into two organizations: Civil Aeronautics Administration (CAA) and Civil Aeronautics Board (CAB).

Since then, CAA has evolved into the Federal Aviation Administration (FAA) and, similarly, CAB has evolved into the National Transportation Safety Board (NTSB). Now, both FAA and NTSB are part of the U.S. Department of Transportation [7]. The current responsibilities of both FAA and NTSB are discussed in the following subsections.

9.5.1 Federal Aviation Administration Responsibilities

The Federal Aviation Administration has many responsibilities. The main ones are shown in Figure 9.1 [7, 15].

9.5.2 National Transportation Safety Board Responsibilities

The National Transportation Safety Board (NTSB) has responsibilities inside and outside the aviation industrial sector. More specifically, in addition to

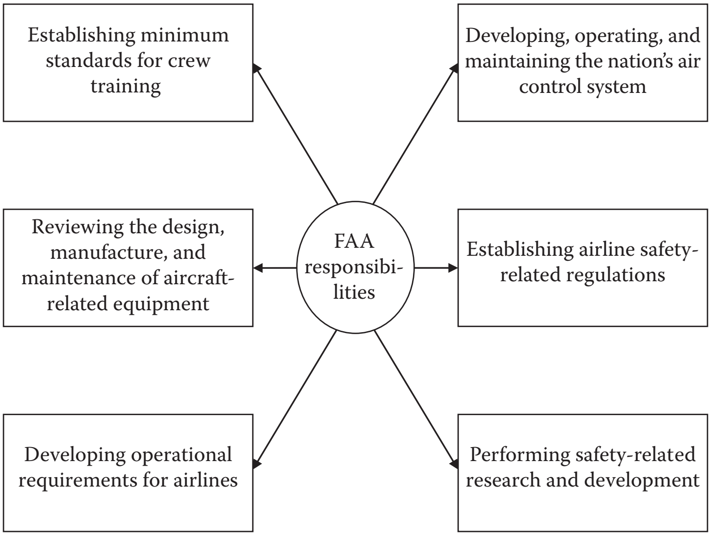

FIGURE 9.1
Federal Aviation Administration (FAA) responsibilities.

investigating aviation-related accidents, the NTSB is also responsible for investigating significant accidents occurring in other modes of transportation, such as marine and railroad. Nonetheless, the main responsibilities of the NTSB are as follows [7]:

- Maintain the government database on aviation-related accidents
- Perform special studies on transportation safety-related issues
- Issue appropriate safety recommendations to help prevent the occurrence of potential accidents
- Serve as the "court of appeals" for FAA-associated matters

9.6 Aviation Recording and Reporting Systems

There are various types of aviation recording and reporting systems used throughout the world. In the United States, there are four major organizations that collect and analyze aviation safety-related data. These organizations are the Federal Aviation Administration (FAA), the National Transportation Safety Board (NTSB), the National Aeronautics and Space Administration (NASA), and the Research and Special Programs Administration (RSPA) [6]. Nonetheless, some of the data systems that can be useful in obtaining aviation safety-related information are as follows [6].

- Accident Incident Data System
- Service Difficulty Reporting System
- Air Operator Data System
- Aviation Safety Analysis System
- Near-Midair Collision Database
- Operational Error Database
- Pilot Deviation Database
- Air Transportation Oversight System (ATOS)
- Aviation Accident/Incident Reporting System
- Aviation Safety Reporting System
- Air Carrier Statistics Database
- International Civil Aviation Organization's (ICAO) Accident/Incident Reporting System (ADREP)
- NTSB Accident/Incident Reporting System

Some of these data systems are described separately in the following subsections.

9.6.1 Accident Incident Data System (AIDS)

The Accident Incident Data System (AIDS) was developed by the FAA, and it contains incident data records for all categories of civil aviation in the United States. The AIDS contains air-carrier-related and general-aviation-related incidents from 1978 and general-aviation-related accidents from 1973 [6]. Incidents in this data system are events that do not satisfy the aircraft-damage or human-injury thresholds contained in the NTSB's definition of an accident.

The information contained in the data system is obtained from various sources, including incident reports on FAA Form 8020-5 [6]. The data in the system are categorized as follows [6]:

- Location information
- Aircraft information
- Operator information
- Narrative
- Findings
- Weather/environmental information
- Pilot information

Additional information on this data system is available in Wells and Rodrigues [6].

9.6.2 Aviation Safety Analysis System

The Aviation Safety Analysis System was developed by FAA, and its databases fall under the four categories shown in Figure 9.2 [6]. These categories are: regulatory data, airworthiness data, operational data, and organizational information.

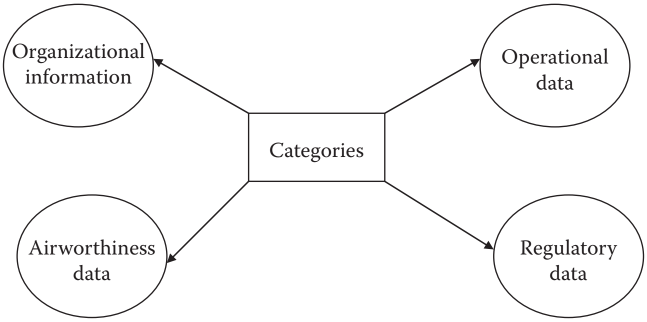

FIGURE 9.2
Aviation Safety Analysis System database categories.

Regulatory data are concerned with background information, such as notices of proposed rule making, legal opinions, and previous regulations. Airworthiness data are mainly concerned with historical information on aircraft, such as FAA-specified mandatory modifications. Operational data are concerned with the aviation environment, such as tracking aircrew, aircraft, and operators along with accidents, incidents, enforcement actions, and mechanical reliability reports. Finally, organizational information is concerned with the work management subsystems to monitor aviation standards tasks, such as airline inspections.

9.6.3 Air Transportation Oversight System (ATOS)

The Air Transportation Oversight System (ATOS) was implemented in 1998 as a modern approach to FAA certification and surveillance oversight, using system safety-related principles and systematic processes for ensuring that the nation's airlines are complying with FAA rules and regulations and have appropriate levels of safety built into their operating systems. The system incorporates items such as the structured application of new inspection-related tasks, analytical processes, and data-collection approaches into the oversight of individual airlines.

Under ATOS, operations of an airline are divided into 7 systems, 14 subsystems, and 88 underlying component elements, which provide a good structure for identifying risks or areas of concern, performing surveillance, and collecting data [6]. Additional information on ATOS is available in Wells and Rodrigues [6].

9.6.4 Accident/Incident Reporting System

The Accident/Incident Reporting System was developed by the National Transportation Safety Board (NTSB), and it contains information on all known civil aviation accidents that have occurred in the United States over the years. This database or system may simply be called the official repository of aviation accident data and causal factors.

The database data are classified under the following nine categories [6]:

- Location information
- Aircraft information
- Sequence of events
- Operator information
- Narrative
- Findings
- Weather/environmental information

- Injury summary
- Pilot information

Additional information on this system is available in Wells and Rodrigues [6].

9.6.5 Aviation Safety Reporting System

The Aviation Safety Reporting System is the result of a joint effort of FAA, National Aeronautics and Space Administration (NASA), and Battelle Memorial Institute, and it is maintained at Battelle Laboratories in Columbus, Ohio. This is a voluntary reporting system, where air traffic controllers, pilots, and others can submit accounts of aviation-related incidents. The system became operational on April 15, 1976, and contains around 500,000 aviation-incident-related reports to date.

The reporting form of the Aviation Safety Reporting System is specifically designed for gathering the maximum amount of information without discouraging reporters. Additional information on the system is available in Wells and Rodrigues [6].

9.6.6 ICAO ADREP System

The International Civil Aviation Organization's (ICAO's) Accident/Incident Reporting System (i.e., ADREP) is a databank that was established in 1970. It contains worldwide civil aviation accident- and incident-related information of aircraft (fixed wing and helicopter) heavier than 5,700 kg. ICAO provides the following information based on this database [6]:

- **ADREP Summary.** This summary contains the ADREP preliminary reports and data reports received by ICAO during a two-month period and is issued six times per year.
- **ADREP Annual Statistics.** This is an ICAO circular that contains annual statistics from the database.
- **ADREP Requests.** These are computer printouts that ICAO provides in response to specific requests from countries.

Additional information on this database is available in the literature [6, 16].

9.7 Noteworthy Marine Accidents

Over the years, there have been many marine accidents. Some of the more noteworthy of these accidents are described in the following subsections.

9.7.1 *Estonia* Accident

The *Estonia* accident is concerned with an Estonian-flagged roll-on-roll (RO-RO) passenger ferry called the *Estonia*. The *Estonia* left Tallinn, the capital city of Estonia, carrying 989 people on board for Stockholm, Sweden, on September 27, 1994, and sank in the northern Baltic Sea in the early hours of September 28, 1994 [17]. The accident resulted in 852 fatalities.

A subsequent investigation into the accident revealed that the bow visor locks were too weak because of their poor design and manufacture. During bad weather, these locks broke, and the visor fell off by pulling open the inner bow ramp [17, 18].

9.7.2 *Derbyshire* Accident

The *Derbyshire* accident is concerned with a very large bulk carrier with a weight of 169,044 dwt (deadweight tons) named *Derbyshire*. The ship, which was en route to Kawasaki, Japan, carrying a cargo of iron ore concentrates, disappeared in puzzling circumstances during a typhoon in the Pacific on September 9, 1980 [17, 18]. The tragedy resulted in 44 fatalities (42 crew members and 2 wives).

The *Derbyshire* was designed in compliance with freeboard and hatch cover strengths as specified in the U.K. government's 1968 regulations [18]. The minimum hatch cover strength requirements for forward hatch covers for bulk carriers of similar size to the *Derbyshire* are considered seriously deficient with respect to the current acceptable safety levels [17].

9.7.3 *Prestige* Accident

The *Prestige* accident is concerned with a 26-year-old Bahamian-registered and American Bureau of Shipping (ABS)-classed single-hull oil tanker, the *Prestige*. The tanker left Riga, Latvia, on November 5, 2002, with a cargo of 77,000 tons of heavy oil. On November 13, 2002, the tanker developed a substantial starboard list in heavy seas and in high winds in the region about 30 nautical miles off the coast of Galicia, Spain [17, 19]. A large crack was discovered in the starboard side of the hull, and the vessel lost its main propulsion and started to drift.

All 27 crew members of the *Prestige* were evacuated safely. On November 19, 2002, the oil tanker broke into two and sank about 133 nautical miles off the coast of Spain. The incident seriously polluted the Spanish coast with oil, and subsequently the European Union (EU) banned single-hull tankers carrying heavy oil from all EU ports [17].

9.7.4 *Herald of Free Enterprise* Accident

The *Herald of Free Enterprise* accident is concerned with a passenger ship called the *Herald of Free Enterprise*. The ship left Zeebrugge Harbour, Belgium, on March 6, 1987, and only four minutes after departure, it capsized and resulted in at least 150 passenger and 38 crew member fatalities [17, 20]. The capsizing of the ship was caused by a combination of adverse factors, including the trim by the bow, the vessel speed, and the bow door being left open.

The public inquiry into the *Herald of Free Enterprise* disaster was an important milestone in ship safety in the United Kingdom. It resulted in actions such as changes to marine safety-related rules and regulations, the introduction of the International Safety Management (ISM) Code for the safe operation of ships and for pollution prevention, and the development of a formal safety assessment process in the shipping industrial sector [17].

9.8 Ship Safety Assessment

The assessment of ship safety has become an increasingly important issue. The techniques of risk and cost-benefit assessments are used in the ship-safety decision-making process. The approach is called a formal safety assessment (FSA) and is composed of the following five steps [17]:

- **Identify hazards.** This step is concerned with the identification of hazards specific to a ship safety-related problem under review. A hazard is defined as a physical situation with the potential for human injury, damage to property, damage to the surrounding environment, or some combination of these.
- **Assess risks.** This step is concerned with estimating risks and factors that influence the level of ship safety. The assessment of risks basically involves studying how hazardous events/states develop and interact to cause an incident/accident.
- **Propose risk control options.** This step is concerned with proposing effective and practical risk-control options. The results of the previous steps are used to identify high-risk areas in order to propose appropriate risk-control measures.
- **Identify benefits from reduced risks and costs.** This step is concerned with the identification of benefits from reduced risks and costs associated with the implementation of each of the previously identified risk-control options.
- **Make decisions.** This step is concerned with making decisions and providing appropriate recommendations for ship safety-related improvements.

9.9 Ship Port-Related Hazards

Over the years, there have been many ship port-related accidents [21]. The ship port-related hazards may be classified under the following categories [21]:

- **Navigation.** The hazards belonging to this category are those that have potential for a deviation of the ship from its intended route or designated channel. Some examples of these hazards are navigation error, pilot error, and vessel not under command.
- **Impacts and collision.** The hazards belonging to this category are concerned with an interaction with a moving or a stationary object, or a collision with a vessel. Some examples of these hazards are vessel collision, berthing impacts, and striking while at berth.
- **Maneuvering.** The hazards belonging to this category are concerned with failure to keep the vessel on the right track or to position the vessel as intended. Two examples of these hazards are fine-maneuvering error and berthing/unberthing error.
- **Loss of containment.** The hazards belonging to this category are concerned with the release and dispersion of dangerous substances. Two examples of these hazards are release of flammables and release of toxic material.
- **Ship related.** The hazards belonging to this category are concerned with ship-specific operations or equipment. Some examples of these hazards are flooding, mooring failure, anchoring failure, and loading/overloading.
- **Environmental.** The hazards belonging to this category are those that occur when weather exceeds vessel design criteria or harbor operations criteria. Some examples of these hazards are extreme weather, strong currents, and winds exceeding port criteria.
- **Pollution.** The hazards belonging to this category are concerned with the release of material that can cause damage to the environment. Two examples of these hazards are crude oil spills and release of other cargo.
- **Fire/explosion.** The hazards belonging to this category are concerned with fire or explosion on the vessel or in the cargo bay. Some examples of these hazards are cargo tank fire/explosion, fire in accommodation, fire in engine room, and other fires.

9.10 Global Maritime Distress Safety System (GMDSS)

GMDSS is based upon a combination of satellite and terrestrial radio services and provides for automatic distress alerting and locating, thereby eliminating the need for a radio operator to send an SOS/Mayday call (a Morse code distress signal). It may simply be characterized as an internationally agreed-upon set of safety-related procedures, equipment types, and communication protocols used for increasing safety and making it easier to rescue distressed ships, boats, and aircraft.

GMDSS is composed of many systems. Some of them are new, and the others have been in operation for many years. The system is intended to carry out the main functions shown in Figure 9.3 [22]. Note that GMDSS also provides redundant means of distress alerting as well as emergency sources of power.

Some of the main types of equipment employed in GMDSS are as follows [22]:

- **Emergency Position-Indicating Radio Beacon (EPIRB).** This equipment/system is designed to operate with the Cospas-Sarsat system, an international satellite-based search-and-rescue system established by Canada, United States, Russia, and France. The automatically activated EPIRBS are designed to transmit to alert rescue-coordination centers via the satellite system from any corner of the world.

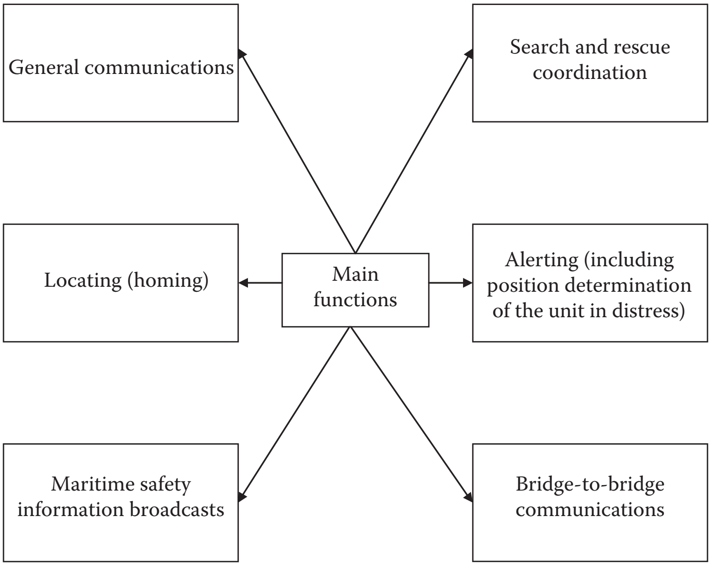

FIGURE 9.3
Global Maritime Distress Safety System (GMDSS) main functions.

- **NAVTEX (Navigational Telex).** This is an international automated system used to distribute maritime navigational-related warnings, search-and-rescue notices, weather forecasts and warnings, and so on.
- **Inmarsat Satellite Systems.** Inmarsat is a British satellite telecommunications company. The satellite systems operated by it and overseen by the International Mobile Satellite Organization (IMSO) are an important element of the GMDSS. The Inmarsat ship–earth-station terminals B, C, and F77 are recognized by the GMDSS.
- **Digital Selective Calling (DSC).** This is a part of the GMDSS system and is basically intended to initiate ship-to-ship, ship-to-shore, and shore-to-ship radiotelephone and MF (medium frequency)/HF(high frequency) radiotelex calls,
- **Search-and-Rescue Transponder (SART) devices.** These devices are used for locating survival craft or distressed vessels by generating a series of dots on the rescuing ship's radar display.

Problems

1. Write an essay on airline and ship safety.
2. Discuss the U.S. airline-related fatalities and accident rate.
3. What are the causes of airplane crashes?
4. What are the main responsibilities of the Federal Aviation Administration (FAA)?
5. List at least 10 data systems that can be useful for obtaining aviation safety-related information.
6. Describe the following two data systems:
    a. Aviation Safety Reporting System
    b. Accident Incident Data System
7. Discuss the following three marine accidents:
    a. The *Derbyshire* accident
    b. The *Estonia* accident
    c. The *Prestige* accident
8. Describe the Global Maritime Distress Safety System (GMDSS).
9. Discuss ship port-related hazards.
10. Describe the formal safety assessment (FSA) approach used to assess safety in the area of shipping.

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10

Human Error in Rail and Road Transportation Systems

10.1 Introduction

Rail and road transportation systems are an important mode of transport throughout the world. Each day, they transport millions of passengers and millions of dollars worth of goods from one point to another. For example, in the United States, the railway system alone comprises approximately 3,000 track terminals and stations that serve over 600 small regional roads and 15 large freight railroads; U.S. revenue from commercial motor vehicle operations is around $400 billion per year [1, 2].

The effectiveness, safety, and reliability of railway and motor vehicles operations depend on factors such as traffic rules, equipment reliability and safety, general and safety management, and human factors. Each year, a large number of railway and motor-vehicle accidents result in many fatalities and a high economic cost due to human factors–related problems around the world [3–5]. Human error in rail and road transportation systems has become an increasingly important issue.

This chapter presents various important aspects of human error in rail and road transportation systems.

10.2 Railway System Human Error–Related Facts, Figures, and Examples

Some railway system human error–related facts, figures, and examples are presented as follows:

- During the period 1900–1997, about 70% of the 141 accidents that occurred on four main railway lines in the United Kingdom were the result of human error [6, 7].

- In 1999, a train accident due to a human error in the United Kingdom resulted in 31 fatalities and 227 injuries [8].
- In 2005, a three-train collision due to a human error in Pakistan resulted in 133 fatalities [9].
- In the United States, approximately 53% of the railway switching-yard accidents (i.e., excluding highway–rail-crossing train accidents) in 2004 were caused by human factors–related problems [3].
- During the period 1970–1998, approximately 62% of the 13 railway accidents in Norway that caused fatalities or injuries were due to human error [7].
- Approximately 66% of over 400 railway accidents that occur in India annually are directly or indirectly due to human error [10].
- A train accident due to a human error at Purley on the London-to-Brighton line in the United Kingdom resulted in 5 fatalities and 88 injuries in 1989 [5].
- In 1988, 30 persons died and 69 were injured seriously in a railway accident due to a human error at the Clapham Junction in the United Kingdom [11].

10.3 Railway Operation–Related Typical Human Error Occurrence Areas

Although there are many areas in railway operation in which human error can occur, the three typical ones are shown in Figure 10.1 [7]. Each of these areas is described in the following subsections.

10.3.1 Train Speed

Over the years, excessive train speed has caused many accidents because of the train driver's failure to reduce speed as specified for the given route.

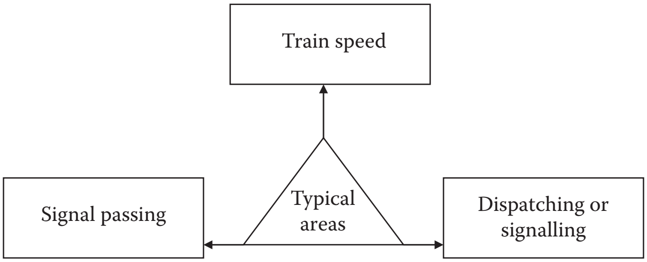

FIGURE 10.1
Typical areas for the occurrence of human error in railway operation.

Some of the factors on which the likelihood of speeding and its associated circumstances depend include the type of speed restrictions and the circumstances around them. There are basically three types of speed restrictions that need input from the driver's perspective:

- **Permanent speed restrictions.** These restrictions are imposed because of track curves or some existing infrastructure-related conditions on a certain section of a rail track.
- **Conditional speed restrictions.** These restrictions are imposed because of a train-route-related setting at a station or junction as well as the state of a traffic signal on the track.
- **Emergency or temporary speed restrictions.** These restrictions are imposed because of track-associated maintenance work or temporary track shortcomings such as frost heave and stability problems.

10.3.2 Signal Passing

A train that passes a stop signal creates a dangerous situation, as it can result in an immediate conflict with other trains. This situation is commonly known as Signal Passed at Danger (SPAD), and some of the main reasons for the occurrence of SPAD are as follows [8]:

- Poor judgment of which signal is applicable to the train in question
- Misjudgment of the brakes' effectiveness under circumstances such as bad weather
- Failure to see signal clearly because of poor visibility
- Unconscious or sleeping driver
- Disregarding a signal
- Misunderstanding a signal
- Speeding without regard to the warning-signal distance and braking performance

Each year, many SPAD-related incidents occur in railway systems around the world. For example, in the United Kingdom alone during the period 1996–1997, there were 653 SPAD-related incidents [8]. A study performed in the Netherlands of SPAD incidents occurring during the period 1983–1984 reported the following findings [7, 12]:

- During the specified period, there were 214 SPAD incidents.
- Approximately 90% of the incidents occurred at marshalling yards or stations, and roughly 50% of them were associated with arrival trains.
- There were basically no differences in the occurrence of SPAD incidents between the various days of the week or the months of the year.

- There appear to be more occurrences of SPAD incidents during the early hours of a work shift than the late hours of the shift.
- There was no correlation between the experience or route knowledge of the train driver and the frequency of SPAD incident occurrences.

10.3.3 Dispatching or Signaling

Over the years, many railway accidents have occurred in the area of dispatching or signaling because of errors made by dispatchers or signalmen. Fortunately, the application of modern technical devices has helped to significantly reduce the occurrence of human error. Additional information on this topic is available in Anderson [7].

10.4 Railway Personnel Error-Prone Tasks and Error-Contributing Factors in Railway Operations

Railway personnel carry out a wide variety of tasks in their day-to-day work environment. All of these tasks are subject to human error, but past experience indicates that some of these tasks are more prone to human error than others. Some of the day-to-day tasks carried out by railway personnel that are prone to serious human error are as follows [8]:

- Engine-driver controlling the train
- Railway personnel maintaining the tracks
- Switching personnel controlling the points
- Railway personnel maintaining the track systems/devices
- Railway personnel maintaining the concerned vehicles
- Railway personnel loading the wagons
- Station supervisor or foreman dispatching the train from the railway station
- Station supervisor or foreman receiving the train into the railway station

There are many error-contributing factors in railway operations. A study of seven Canadian and U.S. Class I freight railroads and several regional roads, concerning all Federal Railroad Administration (FRA) reportable train-related accidents conducted over a period of six months, reported 67 accidents/incidents [2, 3]. Six of these accidents/incidents were studied further with respect to the factors that contribute to the occurrence of errors.

The study highlighted 36 factors that most likely contributed to the occurrence of these six accidents/incidents. These error-contributing factors were categorized under the following four classifications [3]:

- **Operator acts.** This classification contained 12 contributing factors that were further divided into three groups: decision errors, skilled-based errors, and a routine contravention.
- **Supervisory factors.** This classification contained six contributing factors that were further divided into two groups: poor supervision and planned inappropriate operations. The poor supervision was highlighted five times in three of the six accidents/incidents investigated, and the planned inappropriate operations were associated with only one accident/incident.
- **Organizational factors.** This classification contained nine contributing factors that were further divided under two groups: the organizational process and resource management. The organizational process contributing factors were highlighted six times in four of the six accidents/incidents. They were basically concerned with the procedures governing remote-control locomotive (RCL) operations and poor practices. In two of the six accidents/incidents, the application of the RCL technology-resource management was involved, and it was associated with three contributing factors. One of these three factors was inadequate staffing.
- **Preconditions for operator acts.** This classification contained nine contributing factors that were further divided into two groups: the physical environment and the technological environment. Under the physical environment, there was only one contributing factor—poor lighting in the yard—that was concerned with one of the accidents/incidents. A total of eight contributing factors were associated with the technological environment in four of the six accidents/incidents investigated. An example of these eight contributing factors is the inability of the operator to determine the forward direction of the locomotive.

10.5 Checklist of Statements to Reduce Human Error in Railway Operations

This section presents a checklist of statements considered useful in ensuring good human-factors practices in railway-associated projects. In turn, this exercise or action will be helpful in reducing human error in railway operations. These statements are presented in Table 10.1 [2, 13].

TABLE 10.1

Statements To Reduce Human Error in Railway Operations

No.	Statement
1	All human-factors planning aspects are fully and effectively integrated into the general project planning
2	People conducting human factors–related tasks are provided with appropriate resources and authority
3	People conducting human-factors tasks are competent enough to conduct such tasks
4	A coordinator is appointed to coordinate human factors program-wide
5	Each and every dependency between human actions is understood clearly
6	Human factors receive the same importance as any other area of safety engineering
7	Each and every aspect of human factors is considered from the start of a project
8	All aspects of human factors are fully and effectively integrated into the safety argument
9	All human factors–related requirements are fully integrated into the system requirements
10	A broad range of information related to human factors is communicated effectively
11	The existing and necessary end users' competency are evaluated in an effective manner
12	The project aims to design systems to help potential users avoid or recover from all types of hazards
13	Human-error representation is fully integrated with other safety analysis aspects
14	The tasks being performed are understood clearly in order to highlight sources of human error
15	All human-reliability-analysis approaches are used properly and effectively
16	When considering risk-reduction methods, all possible potential users are involved
17	Human errors are identified, modeled, and controlled in an effective manner
18	The identification, evaluation, and reduction of risk from human error is considered as an important component of any safety-associated process
19	The human-error-identification process is effectively integrated into the general hazard identification process, within the project framework

Source: [2, 13].

10.6 Road Transportation Systems Human Error–Related Facts and Figures

Some of the human error–related facts and figures for road transportation systems are as follows:

- The worldwide annual cost of road crashes is about $500 billion, and by the year 2020, road traffic injuries will become the third largest cause of disabilities in the world [14–16].
- Each year, over 40,000 people die and another 3.5 million people are injured in road accidents in the United States. The annual cost of highway crashes to the nation is over $150 billion [17].

- Approximately 65% of motor-vehicle-related accidents are attributable to human error [18].
- About 5,000 truck accident-related deaths occur each year in the United States. Human error is cited more frequently than mechanical problems [19].
- During the period 1966–1998, over 70% of bus accidents were the result of driver error in India, Nepal, Thailand, Tanzania, and Zimbabwe [20].
- Approximately 80% of heavy-truck accidents are due to human error [21].
- Approximately 57% of all bus accidents in South Africa occur due to human error [22].
- In a study by Zogby, Knipling, and Werner [23], most of the car–truck crashes occurred due to human error committed either by the truck driver or the car driver.

10.7 Driver Error Classifications, Common Driver Errors, and Driver Error Ranking

Each day, drivers make various types of errors that can lead to an accident. These errors can be grouped under four distinct classifications. These classifications, in decreasing frequency of occurrence, are as follows [24, 25]:

- Recognition errors
- Decision errors
- Performance errors
- Miscellaneous errors

Additional information on these classifications is available in the literature [24, 25]. As per various studies, the most common driver errors are as follows [26, 27]:

- Following too closely
- Changing lanes abruptly
- Passing or overtaking in the face of incoming traffic
- Following closely prior to overtaking
- Straddling lanes
- Overtaking at crossroad or junction

- Driving too fast for prevailing circumstances
- Following too closely a motor vehicle that is in the process of overtaking

Over the years, various studies have been conducted to rank driver errors from highest frequency of occurrence to the lowest frequency of occurrence [24, 25, 27]. One of these studies ranked driver errors/causes from highest to lowest frequency of occurrence as follows: lack of care; too fast; looked, but failed to see; distraction; inexperience; failure to look; incorrect path; poor attention; improper overtaking; incorrect interpretation; lack of judgment; misjudged distance and speed; following too closely; difficult maneuver; reckless or irresponsible; incorrect decision/action; lack of education or road craft; faulty signaling; and poor skill [27].

10.8 Operational Influences on the Performance of Commercial Drivers

Operational influences play an important role with respect to the occurrence of human error on the part of commercial drivers, who work against the backdrop of a complex operational environment. Four important elements of this complex operational environment are shown in Figure 10.2 [2, 23]. These are work requirements, practices outlined by the company management, labor policies and traditions, and government or other body regulations and penalties for violations.

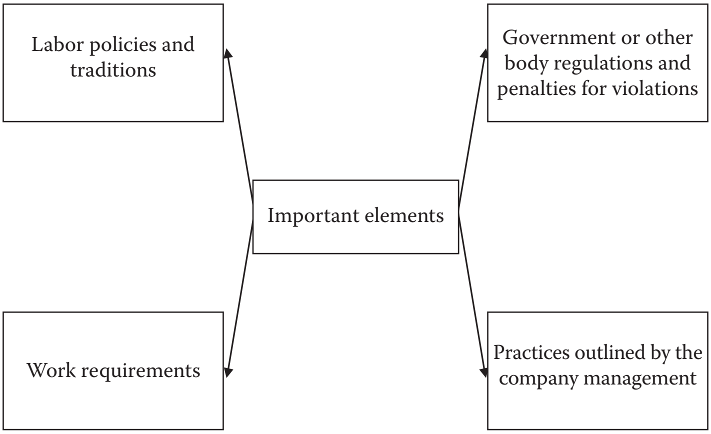

FIGURE 10.2
Important elements of commercial drivers' operational environment.

An example of the work requirements is customer delivery schedules, and the practices outlined by the company management include items such as scheduling, training, and incentives for safe work performance. The remaining two elements—labor policies and government regulation—are considered self-explanatory.

10.9 Bus Accidents and Bus Accident–Related Driver Errors in Selected Developing Countries

Buses are an important mode of transportation around the world. Each year, road accidents account for about 0.8 million fatalities and 20–30 million injuries around the world [2, 20, 28]. About 70% of these events occur in the developing countries. In fact, the fatality rate per registered vehicle in the developing countries is at least 10 to 20 times greater than that of the most highly industrialized countries. A study of road accidents in five developing countries reported the following percentages of bus accidents for the period 1966–1998 [2, 20, 28]:

- 24%: Tanzania
- 15%: Zimbabwe
- 14%: Nepal
- 8%: India
- 5%: Thailand

Similarly, the fatalities per bus accident during the same time period for these five countries were as follows [2, 20, 28]:

- 0.39: Tanzania
- 0.02: Zimbabwe
- 0.76: Nepal
- 0.17: India
- 0.34: Thailand

These figures show that the highest level of bus accidents as a percentage of total road accidents was in Tanzania, and the highest level of fatalities per bus accident was in Nepal. Three main classifications of causes for bus accidents in Tanzania are shown in Figure 10.3 [20, 28]. These classifications are human factors, vehicle condition, and external factors. The percentage breakdowns for these three classifications were 76%, 17%, and 7%, respectively. Clearly, the main cause of bus accidents in Tanzania was human error.

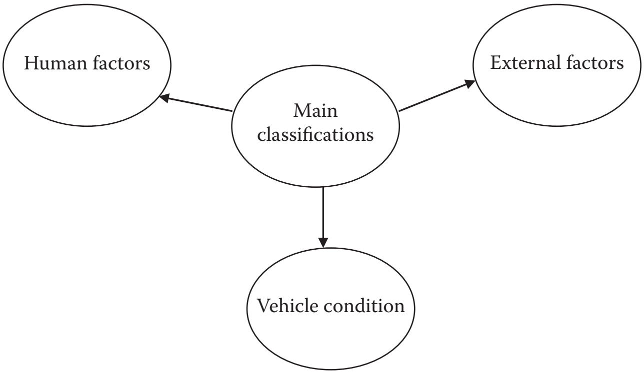

FIGURE 10.3
Main classifications of causes for bus accidents in Tanzania.

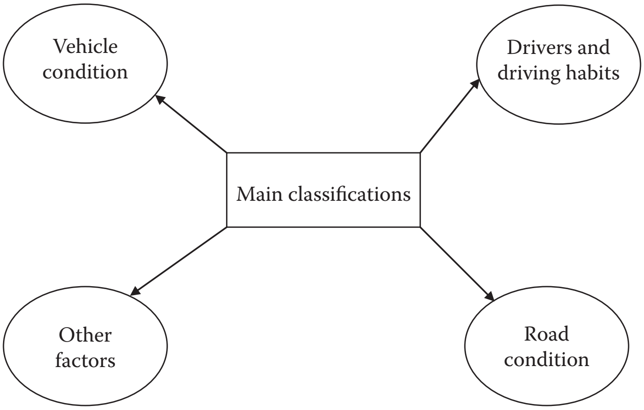

FIGURE 10.4
Main classifications of likely causes for bus accidents in Nepal.

Similarly, the main classifications of likely causes for the occurrence of bus accidents in Nepal are shown in Figure 10.4 [20, 29].

A study of bus accidents in Tanzania, Zimbabwe, Nepal, India, and Thailand for the period 1966–1998 revealed that 70%–80% of bus accidents were the result of driver error [2, 20].

Problems

1. Write an essay on human error in rail and road transportation systems.
2. List at least 10 facts and figures concerned with human error in rail and road transportation systems.
3. Discuss three typical areas for the occurrence of human error in railway operations.

4. What are the day-to-day tasks performed by railway personnel that are prone to serious human error?
5. Discuss error-contributing factors in railway operations.
6. Write down the 10 most-important statements to reduce human error in railway operations.
7. Write down at least eight of the most-common driver errors.
8. Discuss operational influences on the performance of commercial drivers.
9. Discuss bus accidents and bus accident–related driver errors in developing countries.
10. Compare human error in rail and road transportation systems.

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11

Human Error in Aviation and Sea Transportation Systems

11.1 Introduction

Aviation and sea transportation systems have become an important element of the global economy. Each year, over 1.6 billion passengers around the world use airlines for business and leisure travel and over 40% of the world trade of goods is carried by air from one place to another [1]. Furthermore, over 90% of the world's cargo is transported by merchant ships, and there are approximately 90,000 merchant ships in the world [2, 3].

The overall aviation accident rate has declined considerably over the years (the accident rate for air travel is about one fatality per million flights), but the reduction in human error–related accidents in aviation has unfortunately failed to keep pace with the reduction of accidents [4–6]. In fact, as mechanical equipment has become more reliable, humans have become an increasing causal factor in the occurrence of both civilian and military aviation accidents [4, 5].

In regard to sea transportation systems, a modern ship comprises many systems/equipment/parts that require varying degrees of human intervention. About 80% of all accidents in the shipping industry are rooted in human error [7].

This chapter presents various important aspects of human error in aviation and sea transportation systems.

11.2 Aviation Transportation Systems

11.2.1 Human Error in Aviation: Facts, Figures, and Examples

Some of the facts, figures, and examples concerning human error in aviation are as follows:

- A study conducted by Boeing reported that failure of the cockpit crew has been a contributing factor in over 73% of aircraft accidents worldwide [8, 9].
- According to a study reported in *Science Daily* [10], about 45% of all major airline crashes that occur at airports are the result of pilot error. In contrast, pilot error accounts for only 28% of the major crashes that occur elsewhere.
- A study conducted by the National Aeronautics and Space Administration (NASA) reported that, since the introduction of turbojet aircraft in the latter years of the 1950s, over 70% of airline accidents have involved some degree of human error [11].
- A study of major airline crashes in the United States reported that pilot error accounted for 43% of the accidents for the period 1983–1989, decreasing to about 34% for the period 1990–1996 [10].
- According to a study reported in *Science Daily* [10], there were 29,798 general aviation crashes, 1,735 commuter/air-taxi crashes, and 371 major airline crashes during the period 1983–1996. A study of these crashes revealed that pilot error was a probable cause for 38% of major airline crashes, 74% of commuter/air taxi crashes, and 85% of general aviation crashes.
- In 1978, a United Airlines DC-8 aircraft carrying 189 people crashed due to pilot error while landing in Portland, Oregon, resulting in 10 onboard fatalities [11].
- In 1982, an Air Florida Boeing 737 aircraft crashed in Washington, D.C., because the pilot failed to heed to the copilot's repeated warnings that the aircraft was moving too slowly during the acceleration prior to takeoff [11].

11.2.2 Organizational Factors Related to Pilot Error in Commercial Aviation Accidents

Over the years, the occurrence of high-profile accidents such as the space shuttle *Challenger* disaster, the nuclear accident at Chernobyl, and the Piper Alpha oil platform disaster in the North Sea has brought considerable attention to determining the role of organizational factors in the causation of accidents in high-risk systems [12–15]. In particular, considerable emphasis is being placed on organizational factors in the occurrence of aviation accidents, and various studies have been conducted on the role of organizational factors in the occurrence of aviation accidents with respect to pilot error.

One of these studies analyzed the National Transportation Safety Board's (NTSB's) commercial aviation accident data for the period 1990–2000 [12]. The study reported that 60 of the 1,322 accidents that occurred during this period were attributable, directly or indirectly, to pilot error due to 70 organizational causes/factors. These causes/factors were classified into 10 distinct categories, as shown in Figure 11.1 [12]. The figure also shows each of these categories' corresponding brief description in parentheses.

The percentage contributions of the organizational causes/factors belonging to each of the 10 categories shown in Figure 11.1 are as follows [12]:

- 21%: Poor procedures or directives
- 18%: Poor initial, upgrade, or emergency training/transition
- 13%: Poor surveillance of operations

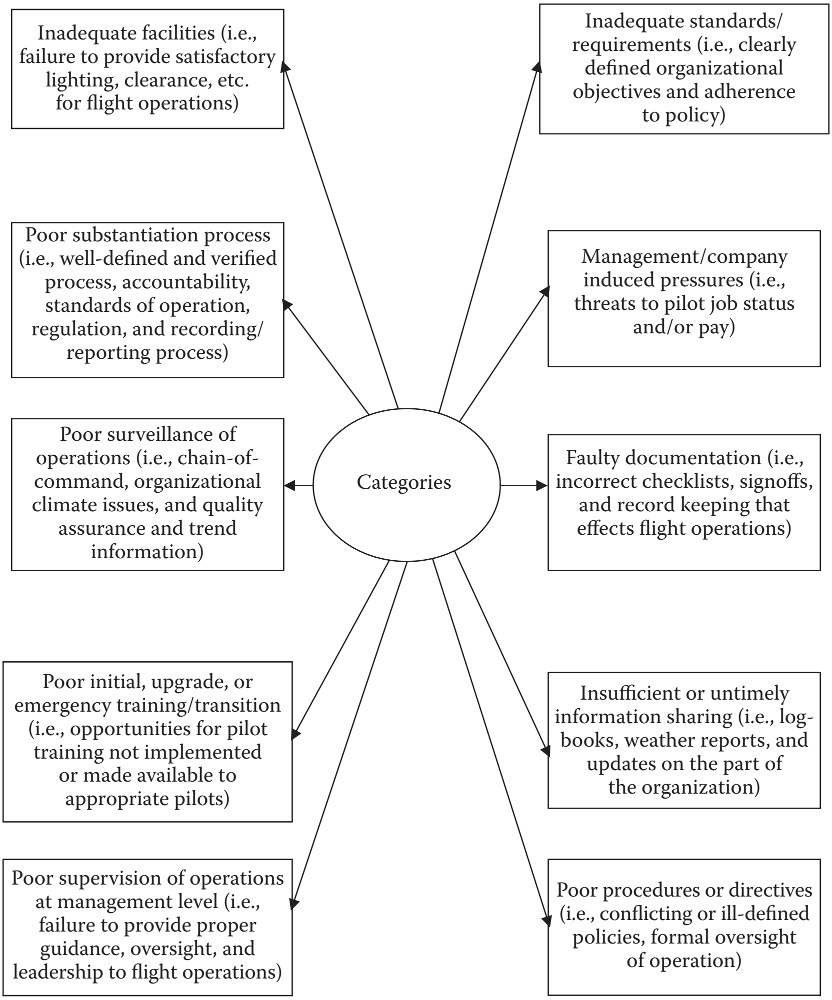

FIGURE 11.1
Categories of organizational causes/factors concerned with the occurrence of pilot error.

- 12%: Insufficient or untimely information sharing
- 12%: Inadequate standards/requirements
- 10%: Poor supervision of operations at management level
- 6%: Management/company-induced pressures
- 4%: Faulty documentation
- 3%: Poor substantiation process
- 1.5%: Inadequate facilities

11.2.3 Flight-Crew Decision Error Contributory Factors

Past experience indicates that there are many factors that can contribute to flight-crew decision errors with respect to the occurrence of incidents. The minimum factors that must be assessed with care in regard to their significance in contributing to flight crew decision errors are shown in Figure 11.2 [16, 17].

The equipment factors include items such as the role of automation, airplane configuration, and airplane flight deck indications. The crew factors include items such as those listed below [16]:

- Crew intention
- Technical knowledge/experience/skills

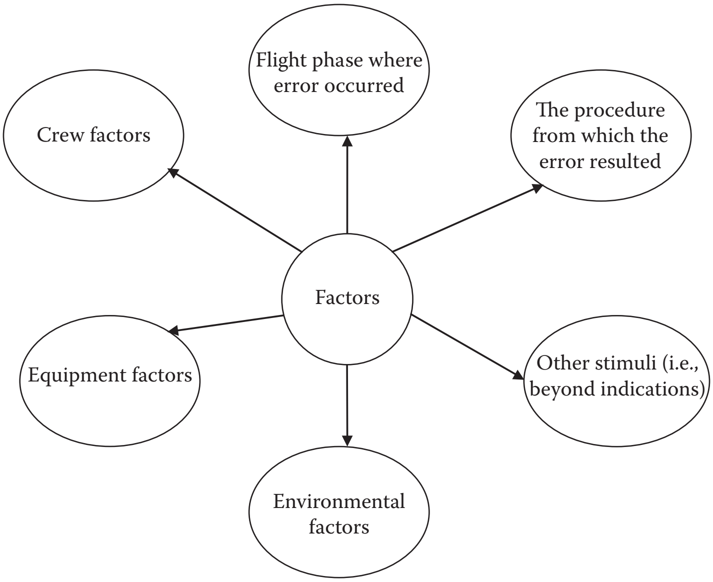

FIGURE 11.2
Minimum factors to be assessed with respect to their significance in contributing to flight crew decision errors.

- Crew understanding of situation at the time of procedure execution
- Crew coordination/communication
- Personal and corporate stressors
- Factors that affect individual performance (e.g., fatigue, workload, etc.)
- Situation awareness factors (e.g., attention, vigilance, etc.)

The factor "The procedure from which the error resulted" includes such items as [16]:

- Crew interpretation of the relevant procedure
- Current guidelines and policies aimed at prevention of incident
- Procedure status
- Onboard source of the procedure
- Procedural factors (e.g., complexity, impracticality, negative transfer, etc.)

The remaining three factors in Figure 11.2 (i.e., environmental factors, flight phase where error occurred, and other stimuli) are considered self-explanatory. Nonetheless, additional information on these factors is available in Graeber and Moodi [16].

11.2.4 Types of Pilot–Controller Communication Errors and Recommendations for Reducing Pilot–Controller Communication Errors

Past experience indicates that the communication between air traffic controllers and pilots is subject to various types of errors. In fact, as per a Federal Aviation Administration (FAA) study of 386 reports submitted to the Aviation Safety Reporting System (ASRS) during the period from July 1991 to May 1996, the pilot–controller communication errors can be grouped into four types [18]:

- **No pilot read-back.** A pilot read-back is probably the best approach for catching miscommunications between pilots and controllers. In this study, no pilot read-back (i.e., the lack of a pilot read-back) accounted for approximately 25% of the total pilot–controller communication errors. The study highlighted the pilot expectation as the most common factor for the occurrence of errors related to no pilot read-back.
- **Read-back/hear-back errors.** A read-back error may be described as a discrepancy between the clearance the air traffic controller issued and the pilot read-back; and in circumstances when the controller fails to rectify this discrepancy, the oversight is called "hear-back error." In this study, read-back/hear-back errors accounted for roughly 47%

of the total pilot–controller communication errors. The study highlighted the similar call signs and controller workload as the most common factor for the occurrence of read-back/hear-back errors.

- **Hear-back errors type II.** These are controller errors in which the pilot correctly repeats the issued clearance, but the controller fails to notice that the issued clearance was not what the controller intended to issue. In this study, this type of error accounted for approximately 18% of the total pilot–controller communication errors.
- **Miscellaneous errors.** These are those errors that cannot be grouped under the above three types of errors. In this study, this type of errors accounted for approximately 10% of the total pilot–controller communication errors.

Some of the recommendations that can be useful in reducing pilot–controller communication errors are as follows [18]:

- Encourage air traffic controllers to treat all types of read-backs as they would treat any other incoming message.
- Encourage controllers to speak distinctly and slowly.
- Encourage controllers to avoid issuing "strings" of instructions to different aircraft.
- In situations when there are similar call signs on the frequency, encourage controllers to continue to announce this fact clearly and accurately.
- Encourage controllers to aim to keep all types of instructions short, with a maximum of four instructions per transmission.
- In situations when there are similar call signs on the frequency, encourage pilots to state their call sign before and after each read-back.
- Encourage pilots to respond to all controller instructions effectively, with a full read-back of all important components/elements.

11.3 Sea Transportation Systems

11.3.1 Human Error in Marine Shipping: Facts, Figures, and Examples

Some of the facts, figures, and examples concerning human error in marine shipping are as follows:

- Approximately 60% of all U.S. Naval Aviation-Class A accidents (i.e., the ones that caused death, permanent disability, or loss of $1 million) were the result of various human and organizational factors [19, 20].

- As per the findings of the U.K. Protection and Indemnity (P&I) Club, human error costs the maritime industry around $541 million annually [21].
- Human error contributes to 84%–88% of tanker-related accidents [22, 23].
- Over 80% of marine accidents are the result of or influenced by organizational and human factors [19, 24].
- A chemical/product tanker named *Bow Mariner* sank in February 2004 because of an onboard explosion due to a human error and resulted in 18 fatalities [25].
- Human error contributes to about 79% of towing vessel groundings [22, 26].
- A study of 6,091 accident claims over $100,000 concerning all classes of commercial ships, conducted by the UK P&I club over a period of 15 years, reported that about 62% of the claims were attributable to human error [21, 27, 28].
- The collision of the MV *Santa Cruz II* and the USCGC *Cuyahoga* due to a human error caused 11 fatalities [22, 29].
- Human error contributes directly or indirectly to 89%–96% of ship collisions [22, 30].
- The grounding of the ship named *Torrey Canyon*, due to various types of human errors, resulted in the spilling of 100,000 tons of crude oil [22, 29].
- A Dutch study of 100 marine casualties reported that human error was a factor in 96 of the 100 accidents [22, 31].

11.3.2 Human Factors–Related Issues Facing the Marine Industrial Sector

There are many human factors–related issues facing the marine industrial sector that influence the occurrence of human error. Some of these issues are as follows [22, 32–36]:

- **Poor automation design.** This is a very challenging issue because poor equipment design pervades almost all shipboard automation. According to Wagenaar and Groeneweg [31], poor equipment design was a causal factor in one-third of all major marine casualties.
- **Fatigue.** This is a quite pressing issue of marine accidents. According to a study reported by McCallum, Raby, and Rothblum [34], fatigue contributed to 33% of the vessel injuries and 16% of the casualties.
- **Faulty policies, practices, or standards.** This issue covers a wide range of problems, including the lack of standard traffic rules from

port to port, lack of available precisely written and comprehensible operational procedures aboard ship, and management policies that encourage risk taking.

- **Poor communications.** This issue is concerned with communications between shipmates, between pilots and masters, ship to ship, and so on. According to the NTSB [36], approximately 70% of major marine collisions and allisions occurred when a state or federal pilot was directing one or both vessels.
- **Poor knowledge of the ship's systems.** This is a frequent contributing factor to marine casualties because of difficulties faced by pilots and crews working on ships of various sizes, with different types of equipment, and carrying different cargoes. A study of a mariner survey reported that 78% of the mariners surveyed cited the lack of ship-specific knowledge to be a major problem [32].
- **Poor general technical knowledge.** This issue is concerned with the mariners' poor understanding of the automation functions or the circumstances under which they were designed to function in an effective manner. According to one study, the problem of improperly using the equipment by the mariners alone was responsible for 35% of casualties [31].
- **Poor maintenance.** This is quite an important issue because poor ship maintenance can result in situations such as dangerous work environments, crew fatigue from the necessity to perform emergency repairs, and lack of functional backup systems.
- **Hazardous natural environment.** This issue is concerned with winds, fogs, and currents that can make for treacherous working conditions and, thus, a greater risk of human error and casualties.
- **Decisions based on inadequate information.** This issue is concerned with mariners making navigation decisions on inadequate information that can result in navigation errors.

11.3.3 Impact of Reduced Manning on Shipping System Reliability and Approaches for Increasing Reliability

The shipping system reliability is impacted negatively and positively in a reduced manning environment. For example, with the human as a system element, the lesser number of humans could very well equate to a reduction in operating capacity. In contrast, the system functions more effectively when equipment/machines or automatic software comprise the system's critical operating parameters. Nonetheless, in the context of improving human reliability, the expected impacts of a reduced manning design on shipping system reliability can be described with regard to the following three human systems integration approaches [17, 37]:

- **Minimize or eliminate human error impacts.** This approach minimizes or eliminates human error impacts through actions such as (a) designing the system to be error tolerant and (b) designing a system that enables the system/human to recognize that an error has occurred and to correct the error prior to the occurrence of any damage.
- **Reduce the occurrence of human error incidence.** This approach reduces human error rates through actions such as job task simplification, error-likelihood modeling or analysis, and application of human engineering design principles.
- **Improve mean time between failures (MTBF) under the reduced manning environment.** This approach improves MTBF through actions such as designing or choosing highly reliable system parts and designing the interfaces to optimize the use of these parts.

11.3.4 Methods for Performing Risk Analysis in Marine Systems

Past experience indicates that there are many sources of risk to marine systems, including equipment failure, human error, institutional error, and external events [17, 38]. Risk analysis is useful to answer the three basic questions presented in Table 11.1 [17].

There are many methods available in the published literature that can be used to perform various types of risk analysis in marine systems. These include fault-tree analysis (FTA), failure modes and effects analysis (FMEA), hazards and operability analysis (HAZOP), preliminary hazard analysis (PHA), interface safety analysis (ISA), probabilistic risk analysis (PRA), event-tree analysis (ETA), safety/review audits, and "what-if" analysis [38–42].

The first five of these methods (i.e., FTA, FMEA, HAZOP, PHA, and ISA) are described in Chapter 4. The remaining ones are briefly described below:

- **Probabilistic risk analysis.** This is a quantitative methodology, and it was developed in the area of nuclear engineering to assess risk. Probabilistic risk analysis may use a combination of risk assessment methods. Additional information on probabilistic risk analysis is available in Bedford and Cooke [43].

TABLE 11.1

Basic Questions Answered by Risk Analysis

Question No.	Basic Question
1	What can go wrong?
2	What are the chances that it will go wrong?
3	What are the expected consequences if it does go wrong?

Source: [17].

- **Event-tree analysis.** This is a quantitative and an inductive modeling method that is used to highlight consequences of all types of events involved, i.e., both successes and failures, that can lead to an accident. Additional information on this method is available in the literature [38, 44].
- **Safety/review audits.** This is a qualitative method for identifying equipment/machine conditions or operating procedures that could lead to a casualty or result in property damage or environmental problems/impacts. Additional information on safety/review audits is available in the literature [38, 41].
- **"What-if" analysis.** This is another qualitative method used to identify hazards, hazardous conditions, or certain accident events that could result in undesirable consequences. Additional information on "what-if" analysis is available in the literature [38, 41, 45, 46].

Problems

1. Write an essay on human error in aviation and sea transportation systems.
2. List at least six human errors in aviation-related facts and figures.
3. Discus organizational factors in commercial aviation-related accidents with respect to pilot error.
4. What are the contributory factors to flight-crew decision error?
5. Discuss pilot–controller communication errors.
6. Discuss useful recommendations to reduce pilot–controller communication errors.
7. List at least seven facts and figures concerned with human error in shipping.
8. What are the human factors–related issues facing the marine industrial sector?
9. Discuss approaches to reduce the manning impact on shipping-system reliability.
10. What are the basic questions answered by risk analysis?

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Bibliography: Literature on the Reliability and Safety of Transportation Systems

Introduction

Over the years, a large number of publications on the reliability and safety of transportation systems have appeared in the form of journal articles, technical reports, conference proceedings articles, and so on. This bibliography presents an extensive list of selected publications related—directly or indirectly—to the reliability and safety of transportation systems.

The period covered by this bibliography is from 1968 till recently. The main objective of this bibliography is to provide readers with additional sources for obtaining information on the reliability and safety of transportation systems.

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Manufacturing and Industrial Engineering

Transportation Systems Reliability *and* Safety

During day-to-day use, thousands of lives are lost each year due to accidents, directly or indirectly, resulting from poor transportation systems reliability and safety. In the United States, automobile accidents alone result in around 42,000 deaths per year, costing billions of dollars to the economy annually. A common subject in journal articles and conference proceedings, most of the recent research on transportation systems reliability and safety is scattered in different resources. Until now.

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