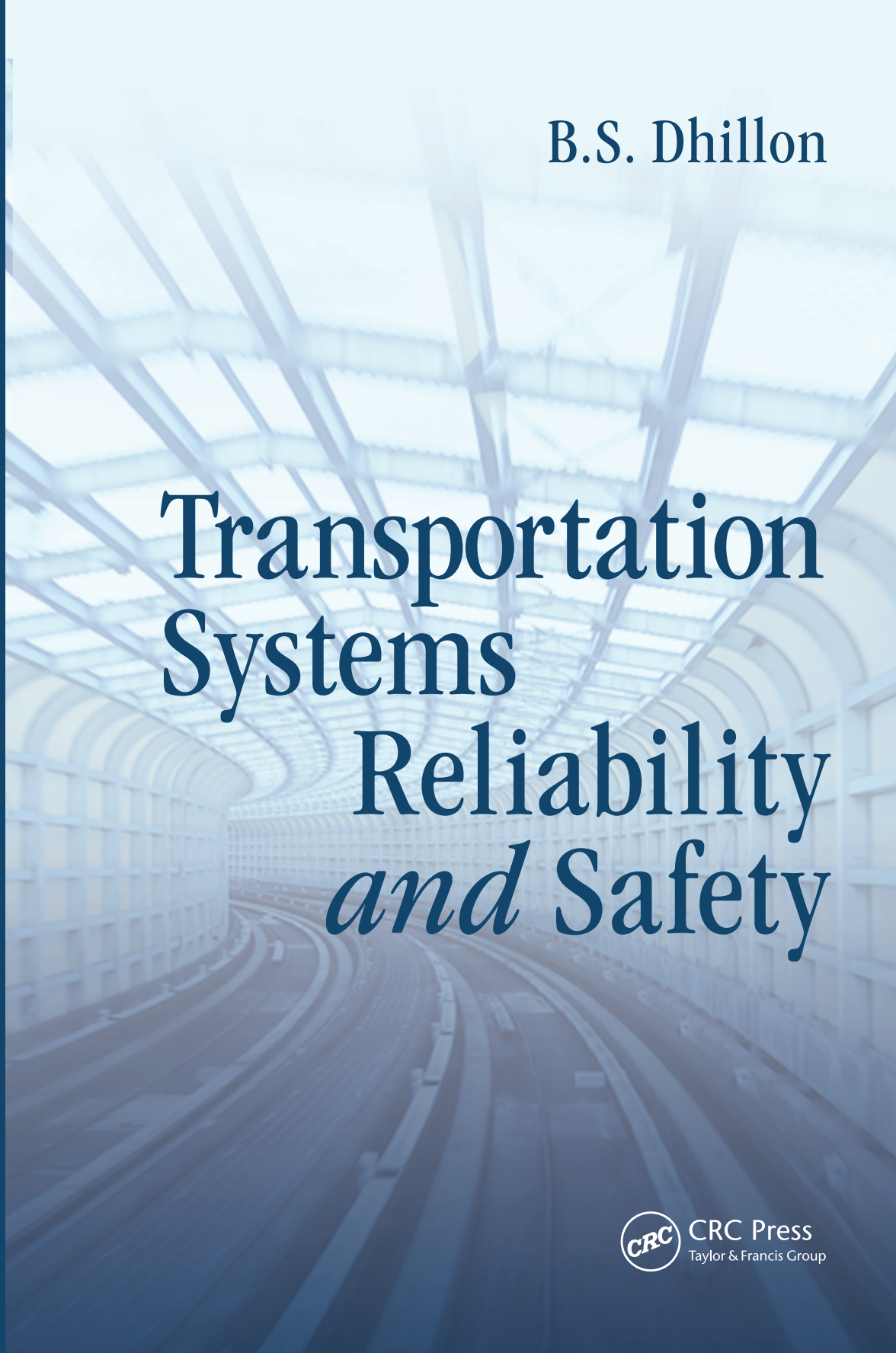
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This book is affectionately dedicated to my son, Mark.

Contents

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
Ottawa, Ontario, Canada

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
- Proceedings of the International Air Safety Seminars
- Proceedings of the International Conference on Automated People Movers, 2001.

1.4.6 Books

- Cox, S. J., *Reliability, Safety, and Risk Management: An Integrated Approach*, Butterworth-Heinemann, New York, 1991.
- Ballard, C., *Safety*, Blackbirch Press, San Diego, California, 2003.
- Shooman, M. L., *Probabilistic Reliability: An Engineering Approach*, McGraw-Hill, New York, 1968.
- Dhillon, B. S., *Design Reliability: Fundamentals and Applications*, CRC Press, Boca Raton, Florida, 1999.
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- Hall, S., *Railway Accidents*, Ian Allan Publishing, Shepperton, U.K., 1997.
- Wells, A. T., and Rodgrigues, C. C., *Commercial Aviation Safety*, McGraw Hill Book Company, New York, 2004.
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- Handley, W., *Industrial Safety Handbook*, McGraw Hill Book Company, New York, 1969.
- Dhillon, B. S., and Singh, C., *Engineering Reliability: New Techniques and Applications*, John Wiley and Sons, 1981. (This book contains a chapter on Transit System Reliability.)
- Goetsch, D. L., *Occupational Safety and Health*, Prentice-Hall, Englewood Cliffs, New Jersey, 1996.
- Dhillon, B. S., *Engineering Safety: Fundamentals, Techniques, and Applications*, World Scientific Publishing, River Edge, New Jersey, 1996.
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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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1 Chapter 1: Introduction

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FIGURE 7.2

Redrawn Fig. 7.1 fault tree with the given and calculated event occurrence probability values.

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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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