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# Human Reliability and Error in Transportation Systems

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B.S. Dhillon

# Human Reliability and Error in Transportation Systems

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# Dedication

This book is affectionately dedicated to all 18th–20th-century late British authors and researchers, including Major General and Sir A. Cunningham, Lt. Colonel J. Tod, Captain R.W. Falcon, Major A.E. Barstow, and Lt. Gen. and Sir G. MacMunn, whose writings helped me to trace my ancient Scythian ancestry, which resulted in the publication of a book on the matter.

# Preface

Today, billions of dollars are being spent annually world wide to develop, manufacture, and operate transportation systems such trains, ships, aircraft, and motor vehicles. During their day-to-day use, thousands of lives are lost due to various types of accidents each year. For example, there were around 1 million traffic deaths and about 40 million traffic injuries worldwide and by 2020, the World Health Organization projects that deaths from accidents will rise to about 2.3 million world wide.

As per some studies, around 70 to 90 percent of transportation crashes are, directly or indirectly, the result of human error. For example, according to a National Aeronautics and Space Administration (NASA) study over 70 percent of airline accidents involved some degree of human error.

Although, the history of the human reliability field may be traced back to the late 1950s, the beginning of the serious thinking on human reliability or error in transportation systems goes back only to the period around the late 1980s. Since the 1980s, over 200 journal and conference proceedings articles on human reliability and error in transportation systems have appeared. However, to the best of the author's knowledge, there is no book on the subject available in the published literature. As the increasing attention is being paid to human error or reliability in transportation systems, the need for a book covering the basics and essentials of general human reliability, errors, factors; and the comprehensive and latest information on human reliability and error in transportation systems, is considered absolutely necessary.

Currently, such information is either available in specialized articles or books, but not in a single volume. This causes a great deal of difficulty to information seekers, because they have to consult many different and diverse sources. This book is an attempt to meet this vital need. The material covered is treated in such a manner that the reader needs no previous knowledge to understand it. The sources of most of the material presented are given in the reference section at the end of each chapter. They will be useful to a reader, if he/she desires to delve deeper into a specific area.

At appropriate places, the book contains examples along with their solutions and at the end of each chapter there are numerous problems to test reader comprehension. This will allow the volume to be used as a text. An extensive list of references on human reliability and error in transportation systems is provided at the end of the book, to give readers a view of the intensity of developments in the area.

The book is composed of 11 chapters. Chapter 1 presents an introductory discussion on human reliability and error in transportation systems, human error in transportation systems-related facts and figures, important human reliability and error terms and definitions, sources for obtaining useful information on human reliability and error in transportation systems, and the scope of the book. Chapter 2 is devoted to mathematical concepts considered useful to perform analysis of human reliability and error in transportation systems and it covers topics such as Boolean algebra laws, probability properties and distributions, and useful mathematical definitions.

Chapter 3 presents introductory human factors including human factors objectives, general human behaviours, human and machine characteristics, human factors data collection sources, and useful human factors guidelines for system design. Basic human reliability and error concepts are covered in Chapter 4. It presents topics such as occupational stressors, human error occurrence reasons and classifications, human performance reliability function, and human reliability and error analysis methods.

Chapter 5 presents a total of nine methods extracted from published literature, considered useful to perform human reliability and error analysis in transportation systems. These methods include fault tree analysis (FTA), the throughput ratio method, technics of operation review (TOR), failure modes and effect analysis (FMEA), Pareto analysis, and the Markov method.

Chapters 6 and 7 are devoted to human error in railways and shipping, respectively. Some of the topics covered in Chapter 6 are railway personnel error prone tasks, important error contributing factors in railways, human error analysis methods, and a useful checklist of statements for reducing the occurrence of human error in railways. Chapter 7 includes topics such as shipping human error related facts, figures, and examples, human factors issues facing the marine industry, risk analysis methods for application in marine systems, fault tree analysis of oil tanker groundings, and reducing the manning impact on shipping system reliability.

Chapter 8 presents various important aspects of human error in road transportation systems. Some of the specific topics covered are operational influences on commercial driver performance, types of driver errors, common driver errors, methods for performing human error analysis in road transportation systems, and bus accidents and driver error in developing countries. Chapter 9 presents various important aspects of human error in aviation including topics such as organizational factors in commercial aviation accidents, factors contributing to flight crew decision errors, types of pilot-controller communication errors, methods for performing human error analysis in aviation, and accident prevention strategies.

Chapters 10 and 11 are devoted to human error in aircraft maintenance and mathematical models for predicting human reliability and error in transportation

systems, respectively. Some of the topics covered in Chapter 10 are reasons for the occurrence of human error in maintenance, major categories of human error in aircraft maintenance and inspection tasks, common error in aircraft maintenance, methods for performing human error analysis in aircraft maintenance, and useful guidelines to reduce human error in aircraft maintenance. Chapter 11 includes topics such as models for predicting human performance reliability and correctability probability in transportation systems, models for predicting human performance reliability subject to critical and non critical human errors and fluctuating environment in transportation systems, and models for performing human error analysis in transportation systems.

This book will be useful to many individuals including system engineers, design engineers, human factors engineers, transportation engineers, transportation administrators and managers, psychology and safety professionals, reliability and other engineers-at-large, researchers and instructors involved with transportation systems, and graduate students in transportation engineering, human factors engineering, and psychology.

The author is indebted to many colleagues and students for their interest throughout this project. The invisible inputs of my children, Jasmine and Mark, are also appreciated. Last, but not least, I thank my wife, Rosy for typing various portions of this book and other related materials, and for her timely help in proofreading and tolerance.

Ottawa, Ontario                                                                 *B.S. Dhillon*

# Contents

# 1

# Introduction

## 1.1 Background

Each year billions of dollars are spent to develop, manufacture, and operate transportation systems such as aircraft, ships, trains, and motor vehicles throughout the world. During their operation, thousands of lives are lost annually due to various types of accidents. For example, in the Untied States around 42,000 deaths occur annually due to automobile accidents alone on highways [1]. In terms of dollars and cents, in 1994 the total cost of motor vehicle crashes, was estimated to be around $150 billion to the United States economy [1, 2].

Needless to say, approximately 70 to 90% of transportation crashes are the result of human error to a certain degree [1]. Moreover, it may be added that human errors contribute significantly to most transportation crashes across all modes of transportation. For example, according to a National Aeronautics and Space Administration (NASA) study over 70% of airline accidents involved some degree of human error and to a British study around 70% of railway accidents on four main lines during the period 1900–1997 were the result of human error [3–5].

Although, the history of human reliability may be traced back to 1958, the beginning of the serious thinking on human reliability or error in transportation systems goes back only to the period around the late 1980s. Since the late 1980s, over 200 journal and conference proceedings publications directly or indirectly related to human reliability or error in transportation systems have appeared. A list of these publications is provided in the Appendix.

## 1.2 Human Error in Transportation Systems Related Facts and Figures

This section presents facts and figures, directly or indirectly, concerned with human reliability and error in transportation systems.

- In 1990, there were about 1 million traffic deaths and around 40 million traffic injuries worldwide; by 2020, the World Health Organization projects that deaths from accidents will rise to around 2.3 million [6, 7].
- Each year over 1.6 billion passengers worldwide travel by air [8].
- The estimated annual cost of world road crashes is in the excess of $500 billion [9].
- Human error costs the maritime industry $541 million per year, as per the findings of the United Kingdom Protection and Indemnity (UKP&I) Club [10].
- In 2004, 53% of the railway switching yard accidents (excluding highway-rail crossing train accidents) in the United States were due to human factors causes [11].
- During the period 1996–1998, over 70% of bus accidents were due to driver error in five developing countries: Thailand, Nepal, India, Zimbabwe, and Tanzania [12].
- As per a Boeing study, the failure of the cockpit crew has been a contributing factor in over 73% of aircraft accidents globally [13, 14].
- Over 80% of Marine accidents are caused or influenced by human and organization factors [15, 16].
- Maintenance and inspection have been found to be factors in around 12% of major aircraft accidents [17, 18].
- In Norway, approximately 62% of the 13 railway accidents that caused fatalities or injuries during the period 1970–1998, were the result of human error [5].
- In India, over 400 railway accidents occur annuall,y and approximately 66% of these accidents are, directly or indirectly, due to human error [19].
- Human error is cited more frequently than mechanical problems in approximately 5,000 truck-related deaths that occur each year in the United States [20].
- A study of car–truck crashes revealed that most of these crashes were due to human error either committed by the truck driver or car driver [21].
- During the period 1983–1996, there were 29,798 general aviation crashes, 371 major airline crashes, and 1,735 commuter/air taxi crashes [22]. A study of these crashes revealed that pilot error was a probable cause for 85% of general aviation crashes, 38% of major airline crashes, and 74% of commuter/air taxi crashes [22].
- As per a study reported in Reference [22], pilot error was responsible for 34% of major airline crashes between 1990 and 1996.
- A study of 6091 major accident claims (*i.e.*, over $100,000) associated with all classes of commercial ships, conducted over a period of 15 years, by the UK P&K Club revealed that 62% of the claims were attributable to human error [10, 23–24].
- Human error contributes to 84–88% of tanker accidents [25, 26].
- A study of data obtained form the United Kingdom Civil Aviation Authority Mandatory Occurrence Report database revealed that maintenance error events per million flights almost doubled over the period 1990–2000 [27].
- In 1979, in a DC-10 aircraft accident due to improper maintenance procedures followed by maintenance personnel, 272 people died [28].

## 1.3 Terms And Definitions

This section presents terms and definitions that are useful to perform human reliability and error analyses in transportation systems [29–33].

- **Transportation system.** This is a facility consisting of the means and equipment appropriate for the movement of goods or passengers.
- **Human reliability.** This is the probability of accomplishing a task successfully by humans at any required stage in system operation within a given minimum time limit (if the time requirement is specified).
- **Human error.** This is the failure to carry out a specified task (or the performance of a forbidden action) that could lead to disruption of scheduled operations or result in damage to property and equipment.
- **Human factors.** This is a study of the interrelationships between humans, the tools they utilize, and the surrounding environment in which they live and work.
- **Accident.** This is an event that involved damage to a specified system or equipment that suddenly disrupts the ongoing or potential system/equipment output.
- **Mission time.** This is that component of uptime required to perform a specified mission profile.
- **Continuous task.** This is a task that involves some kind of tracking activity (*e.g.*, monitoring a changing situation).
- **Redundancy.** This is the existence of more than one means for performing a specified function.
- **Man-function.** This is that function which is allocated to the system's human element.
- **Human performance reliability.** This is the probability that a human will perform all stated human functions subject to specified conditions.
- **Useful life.** This is the length of time an item functions within an acceptable level of failure rate.
- **Consequence.** This is an outcome of an accident (*e.g.*, damage to property, environment pollution, and human fatalities).
- **Failure.** This is the inability of an item to operate within the framework of initially defined guidelines.
- **Human error consequence.** This is an undesired consequence of human failure.
- **Hazardous condition.** This is a situation with a potential to threaten human health, life, property, or the environment.
- **Downtime.** This is the time during which the item is not in a condition to perform its defined mission.
- **Safety.** This is conservation of human life and its effectiveness, and the prevention of damage to items as per mission associated requirements.
- **Unsafe behaviour.** This is the manner in which a person performs actions that are considered unsafe to himself/herself or others.

## 1.4  Useful Information on Human Reliability and Error in Transportation Systems

This section lists journals, conference proceedings, books, technical reports, organizations, and data sources useful for obtaining human reliability and error in transportation systems, directly or indirectly, as well as related information.

### 1.4.1  Journals

Some of the scientific journals that time to time publish articles, directly or indirectly, concerned with human reliability and error in transportation systems, are:

- *Accident Prevention and Analysis*
- *Reliability Engineering and System Safety*
- *Journal of Railway and Transport*
- *Applied Ergonomics*
- *Naval Engineers Journal*
- *Advances in Transport*
- *Ergonomics*
- *International Journal of Man-Machine Studies*
- *Scientific American*
- *Human Factors in Aerospace and Safety*
- *Asia Maritime Digest*
- *Modern Railways*
- *Human Factors and Ergonomics in Manufacturing*
- *Rail International*
- *Marine and Maritime*
- *Human Factors*
- *Advances in Transport*
- *Safety Science*
- *IEEE Transactions on Vehicular Technology*
- *Aeronautical Journal*
- *European Journal of Operational Research*
- *Neural Network World*
- *Canadian Aeronautics and Space Journal*
- *Transportation Research Record*
- *Ocean Engineering*

## 1.4.2  Conference Proceedings

Some of the conference proceedings that contain articles, directly or indirectly, concerned with human reliability and error in transportation systems, are:

- *Proceedings of the Annual Symposium on Reliability*, 1969.
- *Proceedings of the 48th Annual International Air Safety Seminar*, 1995.
- *Proceedings of the IEE International Conference on Human Interfaces in Control Rooms*, 1999.
- *Proceedings of the International Offshore and Polar Engineering Conference*, 1997.
- *Proceedings of the IEEE International Symposium on Intelligent Control*, 2005.
- *Proceedings of the Human Factors and Ergonomics Society Conference*, 1997.
- *Proceedings of the International Conference on Offshore Mechanics and Artic Engineering*, 2001.
- *Proceedings of the International Conference on Automated People Movers*, 2001.
- *Proceedings of the IEEE International Conference on Systems, Man, and Cybernetics*, 1996.
- *Proceedings of the Annual Reliability and Maintainability Symposium*, 2001.


## 1.4.3  Books

Some of the books, directly or indirectly, concerned with human reliability and error in transportation systems, are listed below.

- Whittingham, R.B., *The Blame Machine: Why Human Error Causes Accidents*, Elsevier Butterworth-Heinemann, Oxford, U.K., 2004.
- Wiegman, D.A., Shappell, S.A., A *Human Error Approach to Aviation Accident Analysis*, Ashgate Publishing, Aldershot, U.K., 2003.
- Wells, A.T., Rodgrigues, C.C., *Commercial Aviation Safety*, McGraw Hill Book Company, New York, 2004.
- Reason, J., Hobbs, A., *Managing Maintenance Error: A Practical Guide*, Ashgate Publishing, Aldershot, U.K., 2003.
- Hall, S., *Railway Accidents*, Ian Allan Publishing, Shepperton, U.K., 1997.
- Johnston, N., McDonald, N., Fuller, R., Editors, *Aviation Psychology in Practice*, Ashgate Publishing, Aldershot, U.K., 1994.
- Wiener, E., Nagel, D., Editors, *Human Factors in Aviation*, Academic Press, San Diego, California, 1988.

- Perrow, C., *Normal Accidents: Living with High-Risk Technologies*, Basic Books, Inc., New York, 1984.
- Dhillon, B.S., *Human Reliability: with Human Factors*, Pergamon Press, New York, 1986.

## 1.4.4  Technical Reports

Some of the technical reports, directly or indirectly, concerned with human reliability and error in transportation systems, are as follows:

- Moore, W.H., Bea, R.G., *Management of Human Error in Operations of Marine Systems, Report No. HOE-93-1, 1993*. Available from the Department of Naval Architecture and Offshore Engineering, University of California, Berkeley, California.
- *Human Error in Merchant Marine Safety*, Report by the Marine Transportation Research Board, National Academy of Science, Washington, D.C., 1976.
- McCallum, M.C., Raby, M., Rothblum, A.M., *Procedures for Investigating and Reporting Human Factors and Fatigue Contributions to Marine Casualties*, U.S. Coast Guard Report No. CG-D-09-07, Department of Transportation, Washington, D.C., 1996.
- Report No. DOT/FRA/RRS-22, *Federal Railroad Administration (FRA) Guide for Preparing Accident/Incident Reports*, FRA Office of Safety, Washington, D.C., 2003.
- Treat, J.R., A *Study of Pre-Crash Factors Involved in Traffic Accidents*, Report No. HSRI 10/11, 6/1, Highway Safety Research Institute (HSRI), University of Michigan, Ann Arbor, Michigan, 1980.
- Harvey, C.F., Jenkins, D., Sumner, R., *Driver Error*, Report No. TRRL-SR-149, Transport and Research Laboratory (TRRL), Department of Transportation, Crowthorne, United Kingdom, 1975.
- Report No. PB94-917001, A *Review of Flight-crew-involved, Major Accidents of U.S. Air Carriers, 1978–1990*, National Transportation Safety Board, Washington, D.C., 1994.
- Report No. 5–93, *Accident Prevention Strategies, Commercial Jet Aircraft Accidents, World Wide Operations 1982–1991*, Airplane Safety Engineering Department, Boeing Commercial Airplane Group, Seattle, Washington, 1993.
- Report No. CAP 718, *Human Factors in Aircraft Maintenance and Inspection*, Prepared by the Safety Regulation Group, Civil Aviation Authority, London, U.K., 2002. Available from the Stationery Office, P.O. Box 29, Norwich, U.K.

### 1.4.5 Organizations

There are many organizations that collect human error–related information throughout the world. Some of the organizations that could be useful, directly or indirectly, for obtaining human reliability and error-related information on transportation systems are as follows:

- Transportation Research Board
  2101 Constitution Avenue, NW
  Washington, D.C., USA.
- The Nautical Institute
  202 Lambeth Road
  London, U.K.
- Transportation Safety Board of Canada
  330 Spark Street
  Ottawa, Ontario, Canada.
- U.S. Coast Guard
  2100 Second Street, SW
  Washington, D.C., USA.
- National Research Council
  2101 Constitution Avenue, NW
  Washington, D.C. USA
- Marine Directorate
  Department of Transport
  76 Marsham Street
  London, U.K.
- Federal Railroad Administration
  4601 N. Fairfax Drive, Suite 1100,
  Arlington, Virginia, USA.
- International Civil Aviation Organization
  999 University Street,
  Montreal, Quebec, Canada
- Civil Aviation Safety Authority,
  North Bourne Avenue and Barry Drive Intersection,
  Canberra, Australia.
- Airplane Safety Engineering Department,
  Boeing Commercial Airline Group,
  The Boeing Company,
  7755E. Marginal Way South,
  Seattle, Washington, USA.

## 1.4.6  Data Sources

There are many sources for obtaining human reliability and error-related data. Some of the sources that could be useful, directly or indirectly, to obtain human reliability and error-related data on transportation systems are listed below.

- National Maritime Safety Incident Reporting System, Maritime Administration, Washington, D.C., USA.
- Government Industry Data Exchange Program (GIDEP), GIDEP Operations Center, U.S. Department of Navy, Corona, California, USA.
- NASA Aviation Safety Reporting System, P.O. Box 189, Moffett Field, California, USA.
- Dhillon, B.S., *Human Reliability: With Human Factors*, Pergamon Press, New York, 1986. (This book lists over 20 sources for obtaining human reliability-related data).
- Gertman, D.I., Blackman, H.S., *Human Reliability and Safety Analysis Data Handbook*, John Wiley and Sons, New York, 1994.
- Kohoutek, H.J., Human Centered Design, in *Handbook of Reliability Engineering and Management*, Edited by W. Ireson, C.F. Coombs, and R.Y. Moss, McGraw Hill Book Company, New York, 1996, pp. 9.1–9.30.
- Dhillon, B.S., Human Error Data Banks, *Microelectronics and Reliability*, Vol. 30, 1990, pp. 963–971.
- Stewart, C., *The Probability of Human Error in Selected Nuclear Maintenance Tasks*, Report No. EGG-SSDC-5580, Idaho National Engineering Laboratory, Idaho Falls, Idaho, USA, 1981.
- Boff, K.R., Lincoln, J.E., *Engineering Data Compendium: Human Perception and Performance*, Vols. 1–3, Armstrong Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio, USA, 1988.

## 1.5  Scope of the Book

As in the case of any other engineering system, transportation systems are also subject to human error. In fact, each year thousands of people die due to human error committed in transportation systems, which costs millions of dollars.

Over the years, a large number of publications, directly or indirectly, related to human reliability and error in transportation systems have appeared. Almost all of these publications are in the form of journal or conference proceedings articles, or technical reports. No book provides up-to-date coverage of the subject. This book not only attempts to provide up-to-date coverage of the ongoing effort in human reliability and error in transportation systems, but also of useful developments in the general areas of human reliability, human factors, and human error. More specifically, the book covers fundamentals of human factors, human error, and human reliability in addition to useful techniques and models in these three areas.

Furthermore, the volume provides a chapter on basic mathematical concepts considered useful to understand its contents.

Finally, the main objective of this book is to provide professionals concerned with human reliability and error in transportation systems information that could be useful to reduce or eliminate the occurrence of human error in these systems. This book will be useful to many individuals including system engineers, design engineers, human factors engineers, and other professionals involved with transportation systems; transportation system managers and administrators, safety and psychology professionals, reliability and other engineers-at-large, researchers and instructors involved with transportation systems, and graduate students in transportation engineering and human factors engineering.

## 1.6  Problems

1.  List at least ten facts and figures concerned with human error in transportation systems.
2.  Define the following terms:
    - Transportation system
    - Useful life
    - Human factors
3.  Compare the terms "human error" and "human reliability."
4.  Write an essay on human error in transportation systems.
5.  List five most important journals for obtaining human reliability and error in transportation systems related information.
6.  List at least five sources for obtaining human reliability and error in transportation systems related data.
7.  List four most important organizations for obtaining human reliability and error in transportation systems related information.
8.  Define the following terms:
    - Continuous task
    - Unsafe behaviour
    - Man-function
9.  List at least five important books for obtaining, directly or indirectly, human reliability and error in transportation systems related information.
10. What is the difference between human error and human error consequence?

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3    Helmreich, R.L., Managing Human Error in Aviation, *Scientific American*, May 1997, pp. 62–67.

4    Hall, S., *Railway Accidents*, Ian Allan Publishing, Shepperton, U.K., 1997.

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www.iata.org/pressroom/economics_facts/stats/2003-04-10-01.htm.

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http://www.navy.gov.au/publications/touchdown/dec.04/mainterr.html.

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# 2

# Human Reliability and Error
# Basic Mathematical Concepts

## 2.1 Introduction

The origin of the word "mathematics" may be traced back to the Greek word
"mathema," which means "science, knowledge, or learning." However, our present
number symbols first appeared on the stone columns erected by the Scythian In-
dian Emperor Asoka around 250 B.C. [1, 2]. Over the centuries, mathematics has
branched out into many specialized areas such as pure mathematics, applied
mathematics, and probability and statistics.

Needless to say, today mathematics plays an important role in finding solutions
to various types of science and engineering related problems. Its application ranges
from solving planetary problems to designing systems for use in the area of trans-
portation. Over the past many decades, mathematical concepts such as probability
distributions and stochastic processes (Markov modeling) have also been used to
perform various types of human reliability and error analyses. For example, in the
late 1960s and early 1970s various probability distributions were used to represent
times to human error [3–5]. Furthermore, in the early 1980s, the Markov method
was used to perform various types of human reliability-related analysis [6–8]. This
chapter presents various mathematical concepts considered useful to perform hu-
man reliability and error analyses in transportation systems.

## 2.2 Sets, Boolean Algebra Laws, Probability Definition, and Probability Properties

Sets play an important role in probability theory. A set may simply be described as
any well-defined list, collection, or class of objects. The backbone of the axiomatic
probability is set theory and sets are usually called events. Usually, sets are de-
noted by capital letters A, B, C, …. Two basic set operations are as follows [9–10]:

- **Union of Sets.** The symbol + or U is used to denote union of sets. The union of sets/events, say $M$ and $N$, is the set, say D, of all elements which belong to $M$ or to $N$ or to both. This is expressed as follows:

$$D = M + N. \qquad (2.1)$$

- **Intersection of Sets.** The symbol ∩ or dot (·) (or no dot at all) is used to denote intersection of sets. For example, if the intersection of sets or events $M$ and $N$ is denoted by a third set, say $L$, then this set contains all elements which belong to both $M$ and $N$. This is expressed as follows:

$$L = M \cap N, \qquad (2.2)$$

or

$$L = M \cdot N, \qquad (2.3)$$

or

$$L = M N. \qquad (2.4)$$

The Venn diagram in Fig. 2.1 shows the above case. If there are no common elements between sets $M$ and $N$ (*i.e.*, $M \cap N = 0$), then these two sets are called mutually exclusive or disjoint sets.

Some of the basic laws of Boolean algebra are presented in Table 2.1 [10–11]. Capital letters $M$, $N$, and $Z$ in the table denote sets or events.



$M \cap N$ or $M \cdot N$ or $MN$
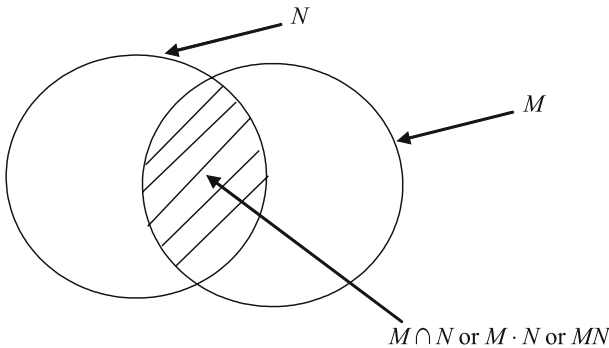
**Figure 2.1.** Venn diagram for the intersection of sets $N$ and $M$

**Table 2.1.** Some basic laws of Boolean algebra

| No. | Law Description | Law |
|---|---|---|
| 1 | Idempotent Laws | $M \cdot M = M$ <br> $M + M = M$ |
| 2 | Absorption Laws | $M(M \cdot N) = M \cdot N$ <br> $M + (M \cdot N) = M$ |
| 3 | Commutative Laws | $M + N = N + M$ <br> $M \cdot N = N \cdot M$ |
| 4 | Distributive Laws | $Z(M+N) = (Z \cdot M) + (Z \cdot N)$ <br> $Z + (M \cdot N) = (Z+M) \cdot (Z+N)$ |

Mathematically, probability is defined as follows [12, 13] :

$$P(X) = \lim_{n \to \infty} \left( \frac{N}{n} \right), \tag{2.5}$$

where

$N$    is the number of times event $X$ occurs in $n$ repeated trials or experiments.

$P(X)$ is the probability of occurrence of event $X$.

The basic properties of probability are as follows [9, 10–12]:

- The probability of occurrence of an event, say $A$, is always

$$0 \le P(A) \le 1. \tag{2.6}$$

- The probability of occurrence and nonoccurrence of an event A is always

$$P(A) + P(\overline{A}) = 1, \tag{2.7}$$

  where

  $P(A)$    is the probability of occurrence of event $A$.

  $P(\overline{A})$    is the probability of nonoccurrence of event $A$.

- The probability of the sample space $S$ is

$$P(S) = 1. \tag{2.8}$$

- The probability of negation of the sample space $S$ is

$$P(\overline{S}) = 0. \tag{2.9}$$

- The probability of union of $n$ independent events $X_1, X_2, X_3, \ldots, X_n$ is expressed by

$$P(X_1 + X_2 + X_3 +, \ldots, + X_n) = 1 - \prod_{i=1}^{n} (1 - P(X_i)), \tag{2.10}$$

  where

  $P(X_i)$    is the probability of occurrence of event $X_i$; for $i = 1, 2, 3, \ldots, n$.

- The probability of union of $n$ mutually exclusive events $X_1, X_2, X_3, \ldots, X_n$ is

$$P(X_1 + X_2 + X_3 +, \ldots, + X_n) = \sum_{i=1}^{n} P(X_i). \tag{2.11}$$

- The probability of intersection of $n$ independent events $X_1, X_2, X_3, \ldots, X_n$ is

$$P(X_1 X_2 X_3 \ldots X_n) = \prod_{i=1}^{n} P(X_i). \tag{2.12}$$

**Example 2.1**

Assume that a transportation system operation task is being performed by two independent individuals: A and B. The task will not be performed correctly if either of the individuals makes an error. The probabilities of making an error by individuals A and B are 0.3 and 0.2, respectively. Calculate the probability that the task will not be accomplished successfully.

Thus for $n = 2$, from Equation (2.10), we get

$$P(A+B) = 1 - (1 - P(A))(1 - P(B)), \tag{2.13}$$

where

$A = X_1$ and $B = X_2$.

By substituting the specified probability values into Equation (2.13), we get

$$P(A+B) = 1 - (1 - 0.3)(1 - 0.2),$$
$$= 0.44.$$

Thus, the probability of not accomplishing the task correctly is 0.44.

## 2.3   Useful Mathematical Definitions

This section presents some mathematical definitions that are considered useful to perform human reliability and error analysis in transportation systems.

### 2.3.1   Cumulative Distribution Function Type I

For continuous random variables, this is defined by [13]

$$F(t) = \int_{-\infty}^{t} f(x)\, dx, \tag{2.14}$$

where

$t$     is a continuous random variable (*e.g.*, time).
$F(t)$   is the cumulative distribution function.
$f(t)$   is the probability density function.

For $t = \infty$, Equation (2.14) yields

$$F(\infty) = \int_{-\infty}^{\infty} f(x)\, dx,$$
$$= 1.$$

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

## 2.3.2  Probability Density Function Type I

For a single-dimension discrete random variable $Y$, the discrete probability function of the random variable $Y$ is represented by $f(y_i)$ if the following conditions apply:

$$f(y_i) \geq 0, \quad \text{for all} \quad y_i \in R_y \text{ (range space)}, \tag{2.15}$$

and

$$\sum_{\substack{\text{all} \\ y_i}} f(y_i) = 1. \tag{2.16}$$

## 2.3.3  Cumulative Distribution Function Type II

For discrete random variables, the cumulative distribution function is defined by

$$F(y) = \sum_{y_i \leq y} f(y_i), \tag{2.17}$$

where
$F(y)$ is the cumulative distribution function.

It is to be noted that the value of $F(y)$ is always

$$0 \leq F(y) \leq 1. \tag{2.18}$$

## 2.3.4  Probability Density Function Type II

For continuous random variables, using Equation (2.14) this is expressed as

$$\frac{d\,F(t)}{dt} = \frac{d\left[\int_{-\infty}^{t} f(x)\,dx\right]}{dt}, \tag{2.19}$$
$$= f(t).$$

## 2.3.5  Expected Value Type I

The expected value, $E(t)$, of a continuous random variable is defined by [12, 13]:

$$E(t) = \mu = \int_{-\infty}^{\infty} t\,f(t)\,dt, \tag{2.20}$$

where
$\mu$     is the mean value.
$t$      is a continuous random variable.
$f(t)$   is the probability density function.

In human reliability work, $\mu$ is known as mean time to human error, and $f(t)$ as probability density of times to human error [14].

## 2.3.6  Expected Value Type II

The expected value, $E(y)$, of a discrete random variable is defined by [12, 13]

$$E(y) = \sum_{i=1}^{n} y_i f(y_i),$$    (2.21)

where
$n$      is the number of discrete values of the random variable $y$.

## 2.3.7  Laplace Transform

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

$$f(s) = \int_{0}^{\infty} f(t) e^{-st} \, dt,$$    (2.22)

where
$t$      is the time variable.
$s$      is the Laplace transform variable.
$f(s)$   is the Laplace transform of $f(t)$.

Laplace transforms of some commonly occurring functions in human reliability work are presented in Table 2.2 [15].

**Table 2.2.** Laplace transforms of selected functions

| $f(t)$ | $f(s)$ |
|---|---|
| $e^{-\lambda t}$ | $1/(s+\lambda)$ |
| $t\,e^{-\lambda t}$ | $1/(s+\lambda)^2$ |
| $\dfrac{d\,f(t)}{dt}$ | $s\,f(s) - f(0)$ |
| c (a constant) | $c/s$ |
| $\displaystyle\int_{0}^{t} f(t)\,dt$ | $f(s)/s$ |
| $t^n$, for $n=0, 1, 2\ 3,\ldots$ | $n!/s^{n+1}$ |

### 2.3.8  Laplace Transform: Final-value Theorem

If the following limits exist, then the final-value theorem may be expressed as follows [16]:

$$\lim_{t \to \infty} f(t) = \lim_{s \to 0} \left[ s f(s) \right]. \tag{2.23}$$

## 2.4  Solving First-order Differential Equations with Laplace Transforms

In performing human reliability and error analyses of transportation systems, solutions to first-order linear differential equations may have to be found. The use of Laplace transforms is considered to be an effective method to find solutions to such equations. The following example demonstrates the application of Laplace transforms to find solution to a system of first order differential equations.

**Example 2.2**
Assume that the following three first-order linear differential equations describe a fluid flow valve being in three distinct states: 0 (working normally), 1 (failed in open mode), 2 (failed in closed mode):

$$\frac{dP_0(t)}{dt} + (\lambda_0 + \lambda_C) P_0(t) = 0, \tag{2.24}$$

$$\frac{dP_1(t)}{dt} - \lambda_0 P_0(t) = 0, \tag{2.25}$$

$$\frac{dP_2(t)}{dt} - \lambda_C P_0(t) = 0. \tag{2.26}$$

At time $t = 0$, $P_0(0) = 1$, and $P_1(0) = P_2(0) = 0$.
The symbols used in Equations (2.24)–(2.26) are defined below.
$P_i(t)$  is the probability that the fluid valve is in state $i$ at time $t$; for
    $i = 0$ (working normally),
    $i = 1$ (failed in open mode), and
    $i = 2$ (failed in closed mode).
$\lambda_0$  is the constant open mode failure rate of the fluid flow valve.
$\lambda_C$  is the constant close mode failure rate of the fluid flow valve.

Find solutions to Equations (2.24)–(2.26) by using Laplace transforms.

By taking Laplace transforms of Equations (2.24)–(2.26) and using initial conditions, we get

$$s\, P_0\left(s\right)+\left(\lambda_0+\lambda_C\right)P_0\left(s\right)=1, \tag{2.27}$$

$$s\, P_1\left(s\right)-\lambda_0\, P_0\left(s\right)=0, \tag{2.28}$$

$$s\, P_2\left(s\right)-\lambda_C\, P_C\left(s\right)=0. \tag{2.29}$$

By solving Equations (2.27)–(2.29), we obtain

$$P_0\left(s\right)=\frac{1}{s+\lambda_0+\lambda_C}, \tag{2.30}$$

$$P_1\left(s\right)=\frac{\lambda_0}{s\left(s+\lambda_0+\lambda_C\right)}, \tag{2.31}$$

$$P_2\left(s\right)=\frac{\lambda_C}{s\left(s+\lambda_0+\lambda_C\right)}. \tag{2.32}$$

Taking inverse Laplace transforms of Equations (2.30)–(2.32) yields

$$P_0\left(t\right)=e^{-\left(\lambda_0+\lambda_C\right)t}, \tag{2.33}$$

$$P_1\left(t\right)=\frac{\lambda_0}{\left(\lambda_0+\lambda_C\right)}\left[1-e^{-\left(\lambda_0+\lambda_C\right)t}\right], \tag{2.34}$$

$$P_2\left(t\right)=\frac{\lambda_C}{\left(\lambda_0+\lambda_C\right)}\left[1-e^{-\left(\lambda_0+\lambda_C\right)t}\right]. \tag{2.35}$$

Thus, Equations (2.33)–(2.35) are the solutions to differential Equations (2.24)–(2.26).

## 2.5 Probability Distributions

There are many discrete and continuous random variable probability distributions. This section presents some of these distributions considered useful for application in performing human reliability and error analyses in transportation systems [17].

### 2.5.1 Binomial Distribution

The binomial distribution is a discrete random variable distribution and is also known as the Bernoulli distribution after its originator, Jakob Bernoulli (1654–1705) [1]. The distribution becomes useful in situations where one is concerned

with the probability of outcome such as the total number of failures or errors in a sequence of, say $n$, trials. However, it is to be noted that the binomial distribution is based upon the reasoning that each trial has two possible outcomes (*e.g.*, success and failure) and the probability of each trial remains constant.

The binomial probability density function, $f(x)$, is defined by

$$f(x)=\binom{n}{i}p^x\,q^{n-x}, \quad \text{for} \quad x=0,1,2,...,\,n, \tag{2.36}$$

where

$$\binom{n}{i}\equiv\frac{n!}{i!(n-i)!}.$$

$x$     is the number of failures in $n$ trials.
$p$     is the single trial probability of success.
$q$     is the single trial probability of failure.

The cumulative distribution function is given by

$$F(x)=\sum_{i=0}^{x}\binom{n}{i}p^i\,q^{n-i}, \tag{2.37}$$

where

$F(x)$   is the cumulative distribution function or the probability of $x$ or less failures in $n$ trials.

The distribution mean is given by [17]

$$\mu_b=n\,p, \tag{2.38}$$

where

$\mu_b$     is the mean of the binomial distribution.

## 2.5.2  Poisson Distribution

This is another discrete random variable distribution, named after Simeon Poisson (1781–1840) [1]. The Poisson distribution is used in situations where one is interested in the occurrence of a number of events that are of the same type. Each event's occurrence is denoted as a point on a time scale, and in reliability work each event represents a failure (error).

The Poisson density function is defined by

$$f(n)=\frac{(\lambda t)^n\,e^{-\lambda t}}{n!}, \quad \text{for} \quad n=0,1,2,..., \tag{2.39}$$

where

$t$     is time.
$\lambda$     is the constant failure, arrival, or error rate.

The cumulative distribution function is given by

$$F = \sum_{i=0}^{n} \frac{(\lambda t)^i \, \mathrm{e}^{-\lambda t}}{i\,!}, \tag{2.40}$$

where

$F$    is the cumulative distribution function.

The distribution mean is given by [17]

$$\mu_\mathrm{p} = \lambda t, \tag{2.41}$$

where

$\mu_\mathrm{p}$    is the mean of the Poisson distribution.


## 2.5.3  Exponential Distribution

The exponential distribution is a continuous random variable distribution and is probably the most widely used distribution in reliability work, because it is relatively easy to handle in performing reliability analysis. Another important reason for its widespread use in the industrial sector is that many engineering items exhibit constant failure rate during their useful life [18].

The distribution probability density function is defined by

$$f(t) = \lambda \, \mathrm{e}^{-\lambda t}, \quad t \geq 0, \quad \lambda > 0, \tag{2.42}$$

where

$f(t)$    is the probability density function.

$\lambda$    is the distribution parameter. In human reliability work, it is known as the constant error rate.

$t$    is time.

By substituting Equation (2.42) into Equation (2.14), we get

$$F(t) = 1 - \mathrm{e}^{-\lambda t}. \tag{2.43}$$

Using Equation (2.42) in Equation (2.20) yields

$$E(t) = \mu = \frac{1}{\lambda}. \tag{2.44}$$

When $\lambda$ is expressed in the term of human errors/unit time (*e.g.*, errors/hour), Equation (2.44) gives mean time to human error (MTTHE).


**Example 2.3**

Assume that the constant error rate of a transit system operator is 0.0005 errors/ hour. Calculate the operator's unreliability for an 8-hour mission and mean time to human error.

By substituting the given data values into Equations (2.43) and (2.44), we get

$$F(8) = 1 - e^{-(0.0005)(8)},$$
$$= 0.004,$$

and

$$E(t) = \mu = 2,000.$$

Thus, the operator's unreliability and mean time to human error are 0.004 and 2,000 hours, respectively.

### 2.5.4  Rayleigh Distribution

The Rayleigh distribution is another continuous random variable distribution and is often used in reliability studies. The distribution is named after John Rayleigh (1842–1919), its originator [1]. The Rayleigh distribution can be used to predict a transit system operator's reliability when his/her error rate increases linearly with time.

The distribution probability density function is defined by

$$f(t) = \frac{2}{\beta^2} t \; e^{-\left(\frac{t}{\beta}\right)^2}, \quad t \geq 0, \;\; \beta > 0,$$

(2.45)

where
$\beta$      is the distribution parameter.

By inserting Equation (2.45) into Equation (2.14), we get

$$F(t) = 1 - e^{-\left(\frac{t}{\beta}\right)^2}.$$

(2.46)

Substituting Equation (2.45) into Equation (2.20) yields

$$E(t) = \mu = \beta \, \Gamma\left(\frac{3}{2}\right),$$

(2.47)

where
$\Gamma(\cdot)$   is the gamma function and is defined by

$$\Gamma(x) = \int_0^\infty t^{x-1} \, e^{-t} \, dt, \quad for \;\; x > 0.$$

(2.48)

### 2.5.5  Weibull Distribution

The Weibull distribution is a continuous random variable distribution that is often used in reliability work. It was developed by W. Weibull (1887–1979), a Swedish

mechanical engineering professor, in the early 1950s [19]. The probability density function of the distribution is defined by

$$f(t)=\frac{b\,t^{b-1}}{\beta^{b}}\,\mathrm{e}^{-\left(\frac{t}{\beta}\right)^{b}}, \quad t\geq0,\ b>0,\ \beta>0,$$

(2.49)

where
$b$ and $\beta$ are the distribution shape and scale parameters, respectively.

By inserting Equation (2.49) into Equation (2.14), we obtain the following cumulative distribution function:

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

(2.50)

Using Equation (2.49) in Equation (2.20), we obtain the following equation for the expected value of $t$:

$$E(t)=\mu=\beta\,\Gamma\!\left(1+\frac{1}{b}\right).$$

(2.51)

For $b=1$ and $b=2$, Equations (2.49)–(2.51) become equations for exponential and Rayleigh distributions, respectively. This simply means that exponential and Rayleigh distributions are the special cases of the Weibull distribution.

## 2.5.6 Gamma Distribution

The gamma distribution is a two-parameter distribution that is quite flexible to study a wide variety of problems including those of human reliability and errors. The distribution probability density function is defined by [16]:

$$f(t)=\frac{\lambda(\lambda t)^{b-1}}{\Gamma(b)}\,\mathrm{e}^{-\lambda t}, \quad t\geq0,\ b>0,\ \lambda>0,$$

(2.52)

where
$\Gamma(\cdot)$    is the gamma function.
$b$ and $\lambda$ are the distribution shape and scale parameters, respectively.

Using Equations (2.14) and (2.52), we get the following cumulative distribution function:

$$F(t)=1-\sum_{i=0}^{b-1}\frac{\mathrm{e}^{-\lambda t}(\lambda t)^{i}}{i!}.$$

(2.53)

By substituting Equation (2.52) into Equation (2.20), we get the following expression for the expected value of $t$:

$$E(t)=\mu=\frac{b}{\lambda}.$$

(2.54)

It is to be noted that for $b=1$, the gamma distribution becomes the exponential distribution.

## 2.5.7  Log-normal Distribution

The log-normal distribution is another two-parameter distribution that can be used to represent times to operator errors. The distribution probability density function is defined by

$$f(t) = \frac{1}{\left(\sqrt{2\pi}\right)t\,\alpha} \exp\left[-\frac{(\ln t - m)^2}{2\,\alpha^2}\right], \quad t \geq 0, \tag{2.55}$$

where
$\alpha$ and $m$ are the distribution parameters.

Using Equation (2.55) in Equation (2.14) yields

$$F(t) = \frac{1}{\left(\sqrt{2\pi}\right)\alpha} \int_0^t \frac{1}{x} \exp\left[-\frac{(\ln x - m)^2}{2\,\alpha^2}\right] dx. \tag{2.56}$$

Letting $w = \dfrac{(\ln t - m)}{\alpha}$, we get

$$\frac{dw}{dx} = \frac{1}{\alpha x}. \tag{2.57}$$

Therefore,

$$dw = \frac{dx}{\alpha x}. \tag{2.58}$$

Using Equations (2.57) and (2.58) in Equation (2.56), we get

$$F(t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\frac{(\ln t - m)}{\alpha}} \exp\left[-\frac{w^2}{2}\right] dw. \tag{2.59}$$

## 2.5.8  Normal Distribution

The normal distribution is a well known distribution that is also known as the Gaussian distribution after Carl Friedrich Gauss (1777–1855), a German mathematician. The probability density function of the distribution is defined by

$$f(t) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(t-\mu)^2}{2\sigma^2}\right], \quad -\infty < t < +\infty, \tag{2.60}$$

where
$\mu$ and $\sigma$ are the distribution parameters known as mean and standard deviation, respectively.

By substituting Equation (2.60) into Equation (2.14), we get the following equation for the cumulative distribution function:

$$F(t) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{t} \exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right] dx. \tag{2.61}$$

Using Equation (2.60) in Equation (2.20), we get the following equation for the expected value of $t$:

$$E(t) = \mu. \tag{2.62}$$

## 2.6  Problems

1. Write an essay on the history of mathematics including probability theory.
2. Draw a Venn diagram showing two mutually exclusive sets.
3. Prove the following Boolean expression:

$$(Z+M)\cdot(Z+N) = Z+(M\cdot N) \tag{2.63}$$

   where

   Z, M, and N are events or sets.
4. A transportation system operation task is being performed by two independent persons $X$ and $Y$. The task will not be performed correctly if either person makes an error. The probabilities of making an error by persons $X$ and $Y$ are 0.4 and 0.1, respectively. Calculate the probability that the task will not be accomplished successfully.
5. Write down definitions for Laplace transform and probability.
6. Obtain Laplace transform for the following function:

$$f(t) = t\,e^{-\lambda t}, \tag{2.64}$$

   where

   $t$ is time.

   $\lambda$ is a constant.
7. Prove Equation (2.23).
8. Assume that the constant error rate of a transit system operator is 0.0001 errors/hour. Calculate the operator's unreliability for an 10-hour mission and mean time to human error.
9. Prove Equation (2.51).
10. Prove Equation (2.53).

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# 3

# Introductory Human Factors

## 3.1 Introduction

The field of human factors exists because humans make errors in using systems or machines; otherwise, it would be rather difficult to justify its existence. Human factors may simply be described as the body of knowledge concerned with human abilities, shortcomings, and so on.

The history of human factors may be traced back to Frederick W. Taylor who in 1898 conducted various studies to determine the most effective design of shovels [1]. In 1911, Frank B. Gilbreth, a devout follower of Taylor's works, studied the problem of bricklaying and invented the scaffold that allowed bricklayers to perform their task at the most appropriate level at all times [2, 3]. As the result of this invention, the bricklaying rate increased from 120 bricks per hour to 350 bricks per hour.

In 1924, the National Research Council (NRC) initiated a study concerned with examining various aspects of human factors at the Hawthorne Plant of Western Electric in the State of Illinois. By 1945, human factors became to be recognized as a specialized discipline, and in 1972 the United States Department of Defense released a document on human factors [4]. This document contained requirements for manufacturers or contractors engaged in developing equipment to be used by the services. Currently, there are a vast number of published documents available on human factors in the form of books, technical reports, and articles.

This chapter presents various fundamental aspects of human factors considered useful for studying human reliability and error in transportation systems.

## 3.2 Human Factors Objectives, Disciplines Contributing to Human Factors, and Human and Machine Characteristics

There are many objectives of human factors. They can be divided into four categories as shown in Figure 3.1 [5]. Category I objectives (*i.e.*, fundamental operational objectives) are concerned with reducing errors, increasing safety, and improving system performance. Category II objectives (*i.e.*, objectives affecting reliability and maintainability) are concerned with increasing reliability, improving maintainability, reducing training requirements, and lowering the need for manpower.

Category III objectives (*i.e.*, objectives affecting users and operators) are concerned with increasing user acceptance and ease of use, improving the work environment; reducing fatigue, physical stress, boredom, and monotony; and increasing aesthetic appearance. Finally, Category IV objectives (*i.e.*, miscellaneous objectives) are concerned with items such as increasing production economy and reducing losses of time and equipment.

Human factors is a multidisciplinary field. There are many disciplines that contribute to it. Some of these disciplines are as follows [5]:

- Psychology
- Engineering
- Anthropometry
- Applied physiology
- Industrial design
- Environmental medicine
- Operations research
- Statistics
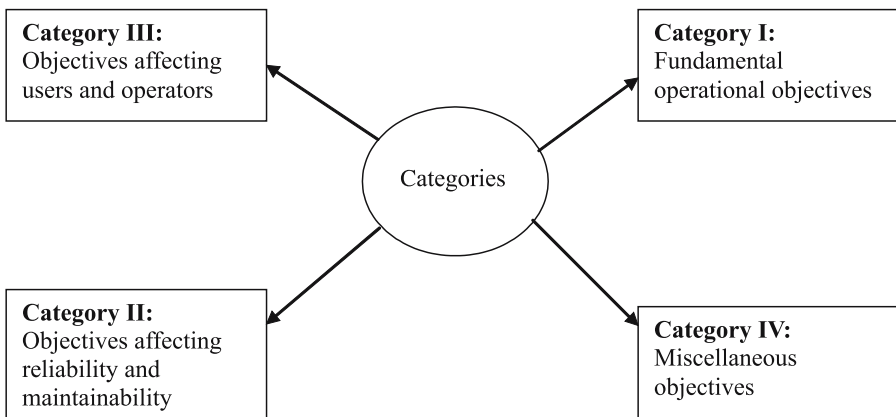


**Figure 3.1.** Human factors objective categories

Humans and machines possess many characteristics. Some of the important comparable human and machine characteristics are presented below [6].

**Human**
- Humans need some degree of motivation.
- Humans possess inductive capabilities.
- Human reaction time is slow in comparison to that of machines.
- Human consistency can be low.
- Humans have a high degree of intelligence, and are quite capable of applying judgments in solving unexpected difficulties or problems.
- Humans are subject to fatigue that increases with the number of hours worked and decreases with rest.
- Humans are significantly affected by environmental factors such as noise, temperature, and hazardous materials, as well as they require air to breathe.
- Human memory could be constrained by elapsed time, but it has no capacity limitation problem.
- Humans may be absent from work due to various factors including illness, strikes, training, and personal matters.

**Machine***
- Machines need no motivation.
- Machines have a rather poor inductive capability, but a quite good deductive ability.
- Machines possess a fast reaction time to external signals.
- Machines are quite consistent, unless there are malfunctions or failures.
- Machines have rather limited intelligence and judgmental capability.
- Machines are free from fatigue, but need periodic maintenance.
- Machines are not easily affected by the environment, thus they are quite useful for applications in unfriendly environments.
- The machine memory is not influenced by absolute and elapsed times.
- Machines are subject to failures.

## 3.3  General Human Behaviors and Human Sensory Capabilities

Past experiences indicate that human behavior plays a crucial role in the success of an engineering system. Therefore, it is important that during the design phase typical

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* It is to be noted that some of the characteristics listed below may be more applicable to robots than to general machines.

human behaviors must be considered with utmost care. Some of the typical human behaviors are as follows [7, 8]:

- Humans are often quite reluctant to admit mistakes.
- Humans often overlook or misread instructions and labels.
- Most people fail to recheck specified procedures for mistakes.
- Humans frequently respond irrationally in emergency situations.
- Humans normally carry out tasks while thinking about other things.
- Humans are normally poor estimators of clearance, distance, and speed.
- A significant proportion of humans become quite complacent after successfully handling hazardous or dangerous items over a long period of time.
- People frequently use their hands first to test or explore.
- People get easily confused with unfamiliar things.
- Generally, people regard manufactured items as being safe.
- Usually humans tend to hurry at one time or another.
- People expect electrically powered switches to move upward, to the right direction, *etc.* to turn power on.

Humans possess many senses: hearing, smell, touch, sight, and taste. More specifically, humans can sense temperature, vibration, rotation, pressure, position, acceleration (shock), and linear motion. Furthermore, a minute deviation in these sensations over a wide range is recognizable by humans.

Four human sensory-related capabilities shown in Figure 3.2 are described below, separately [9, 10].
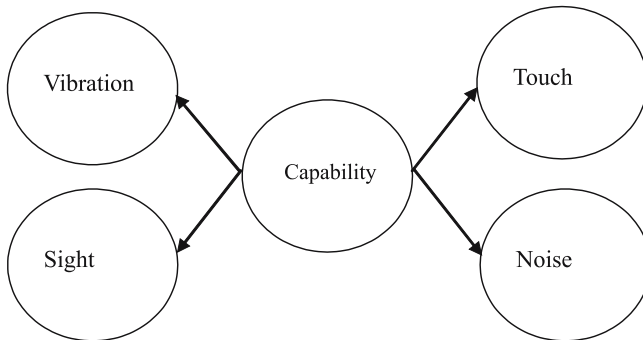


**Figure 3.2.** Four human sensory-related capabilities

**Sight**
Sight is stimulated by electromagnetic radiation of certain wavelengths, often known as the visible segment of the electromagnetic spectrum. The various parts of the spectrum, as seen by the eye, appear to vary in brightness. Also, human eyes

see differently from different angles. The color perception decreases with the increase in the viewing angle.

During the design phase a careful attention should be given to factors such as follows [9]:

- Color makes very little difference in the dark.
- Human eyes, in the daylight, are most sensitive to greenish-yellow light with a wavelength of about 5500 Angstroms.
- Lights for warning purposes should be as close to red in color as possible.
- Use red filters, whenever permissible, with a wavelength greater than 6500 Angstroms.
- Do not place too much reliance on color when critical tasks to be performed by fatigued persons.
- Choose colors in such way that color-weak individuals do not get confused.

**Touch**

This is an important human sense that helps to relieve the load on eyes and ears by conveying messages to the brain. One example of this important human sense is that a person can recognize the shapes of different control knobs just by touching. Nonetheless, the touch sensor has been used by different craft workers for many centuries to detect surface roughness and irregularities in their work output. As per Reference [10], the detection accuracy of surface irregularities improves quite dramatically when a person moves an intermediate piece of thin cloth or paper over the object surface instead of just bare fingers.

**Vibration**

Vibrations may degrade the mental and task performance of a person. In fact, vibrations of large amplitude and low frequency contribute to factors such as eye strain, headaches, fatigue, motion sickness, and deterioration in ability to read and interpret instruments [11]. Some useful guidelines for reducing vibration and motion effects are listed below [12, 13].

- Eliminate vibrations with amplitudes greater than 0.08 mm for performing critical maintenance or other operations requiring letter or digit discrimination.
- Reduce vertical vibrations, since they affect seated personnel most.
- Eliminate or minimize shock and vibrations through design efforts and/or using items such as springs, shock absorbers, and cushioned mountings.
- Avoid any seating design that would result in or would transmit a 3 or 4 cycles per second vibration, since the resonant frequency of the human vertical trunk, in the seated position, is somewhere between 3 and 4 cycles per second.

**Noise**

Noise may simply be described as a sound that lacks coherence. Humans react in various ways to noise including fatigue, boredom, and feelings such as well-being.

Excessive noise may lead to problems such as loss in hearing if exposed for long periods, reduction in the workers' efficiency, and adverse effects on work requiring a high degree of muscular coordination or intense concentration.

A noise level below 90 decibels (dB) is considered to be safe for human beings and levels above 90 dB are unsafe for human beings. In fact, noise levels above 130 dB are considered unpleasant and may actually be painful. Finally, it is added that above-normal noise may make verbal communications, say between operators and maintenance personnel, impossible and may even damage their hearing [11].

## 3.4  Useful Human Factors-related Formulas

Over the years researchers have developed many mathematical formulas to estimate human factors-related information. This section presents some of these formulas considered useful for performing human reliability and error analysis in transportation systems.

### 3.4.1  Formula I: Rest Period Estimation

The formula for rest period estimation is concerned with estimating the total amount of rest (scheduled or unscheduled) required for any given work activity [14]. Thus, the total rest, $TR$, required in minutes is expressed by

$$TR = \frac{TAWT\left(ACE - LEE\right)}{\left(ACE - \theta\right)}, \qquad (3.1)$$

where
$TAWT$    is the total amount of working time expressed in minutes.
$\theta$       is the approximate resting level expressed in kilocalories per minute with its value taken as 1.5.
$ACE$    is the average kilocalories expenditure per minute of work.
$LEE$    is the level of energy expenditure expressed in kilocalories per minute, adopted as standard.

**Example 3.1**
Assume that a transportation system operator is performing a task for 150 minutes and his/her average energy expenditure is 6 kilocalories per minute. Calculate the length of the required rest period, if $LEE = 5$ kilocalories per minute.

By substituting the given data values into Equation (3.1), we get

$$TR = \frac{150\left(6 - 5\right)}{6 - 1.5},$$
$$= 33.3 \ \text{minutes}$$

Thus, the length of the required rest period is 33.3 minutes.

### 3.4.2  Formula II: Maximum Safe Car Speed Estimation

Maximum safe car speed estimation is concerned with estimating the maximum speed of a car on a traffic-free straight highway. The maximum safe speed is expressed by [15]

$$MSS = \frac{HW - CW - 2\,D_{\mathrm{m}} - (CL)(MA)}{(MA)(DRT)},$$
(3.2)

where
$MSS$  is the maximum safe speed.
$HW$  is the highway width.
$CW$  is the car width.
$D_{\mathrm{m}}$  is the car's minimum safe distance from the pavement edge.
$CL$  is the car length.
$MA$  is the mean angle by which the direction of the vehicle under study sometimes deviates from the actual course.
$DRT$  is the driver reaction time.

### 3.4.3  Formula III: Inspector Performance Estimation

Inspector performance estimation is concerned with measuring inspector performance associated with inspection tasks. The inspector performance is expressed by [9, 16].

$$IP = \frac{TIT}{(NPI - NIE)},$$
(3.3)

where
$IP$  is the inspector performance expressed in minutes per correct inspection.
$TIT$  is the total reaction time.
$NPI$  is the number of patterns inspected.
$NIE$  is the number of inspector errors.

### 3.4.4  Formula IV: Character Height Estimation

Character height estimation is concerned with calculating the optimum character height by considering factors such as the viewing distance, the importance of reading accuracy, and viewing conditions. The character height is expressed by [17, 18]

$$CH = (0.0022)(VD) + CF_1 + CF_2,$$
(3.4)

where
$CH$  is the character height expressed in inches.
$VD$  is the viewing distance expressed in inches.

$CF_2$  is the correction factor for the criticality of the number. For important items such as emergency labels, its recommended value is 0.075, and for other items $CF_2 = 0$.

$CF_1$  is the correction factor for illumination and viewing conditions. Its recommended values for different conditions are 0.26 (below 1 foot candle, unfavorable reading conditions), 0.06 (above 1 foot candle, favorable reading conditions), 0.16 (above 1 foot candle, unfavorable reading conditions), and 0.16 (below 1 foot candle, favorable reading conditions).

**Example 3.2**
Assume that the estimated viewing distance of an instrument panel is 40 inches. Calculate the height of the label characters to be used at the panel, if the values of $CF_1$ and $CF_2$ are 0.26 and 0.075, respectively.

By substituting the given data values into Equation (3.4), we obtain

$$CH = (0.0022)(40) + 0.26 + 0.075,$$
$$= 0.423 \text{ inches.}$$

Thus, the height of the label characters to be used is 0.423 inches.

## 3.4.5  Formula V: Brightness Contrast Estimation

Brightness contrast estimation is defined by [9]

$$BC = \frac{(LB - LD)(100)}{LB}, \tag{3.5}$$

where
$BC$   is the brightness contrast.
$LB$   is the luminance of the brighter of two contrasting areas.
$LD$   is the luminance of the darker of two contrasting areas.

**Example 3.3**
Assume that a certain type of paper has a reflectance of 90%. Calculate the value of the brightness contrast, if the print on the paper has a reflectance of 10%.

By substituting the specified data values into Equation (3.5), we get

$$BC = \frac{(90 - 10)(100)}{90},$$
$$= 88.88\%.$$

Thus, the value of the brightness contrast is 88.88%.

### 3.4.6 Formula VI: Glare Constant Estimation

Glare constant estimation is defined by [18]

$$GC = \frac{(SA)^{0.8}(SL)^{1.6}}{(LGB)(AN)^2}$$

where
$GC$   is the glare constant.
$SA$    is the solid angle substended by the source at the eye.
$SL$    is the source luminance.
$LGB$ is the luminance of the general background.
$AN$   is the angle between the glare source direction and the viewing direction.

   It is to be noted that $GC = 35$ means the boundary of "just acceptable" glare, and $GC = 150$ means the boundary of "just uncomfortable" glare.

## 3.5 Human Factors Considerations in the System Design and Their Advantages

It is absolutely essential to carefully consider human factors during the design phase to have an effective human compatible system/product. During the design phase the main objective should be to design a system that allows humans to perform in the most effective manner. More specifically, the system possesses adaptability to humans and it does not subject humans to extreme mental or physical stress or to hazards.

   As the system design phase may be divided into four stages as shown in Figure 3.3, design associated professionals should consider human factors from different perspectives at each of these stages [8]. During the preconceptual stage, the
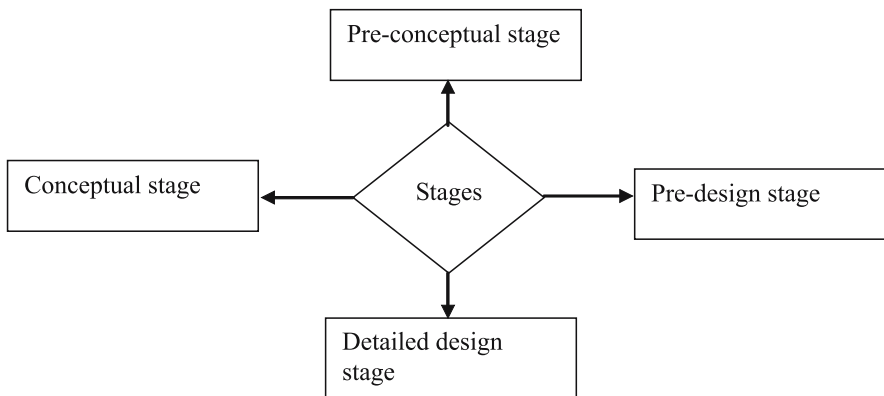


**Figure 3.3.** System design phase stages

design-associated professionals should systematically define items such as the mission and operational requirements, the functions required to perform each mission event, the performance requirements for each function, and the allocation of functions to hardware, human, or software elements.

Similarly, during the conceptual stage, the design-associated professionals should include items such as preliminary task descriptions of operators, users, and maintainers; preliminary definition of manning and training requirements; and analyses for defining the most effective design method to accomplish each hardware functional assignment.

During the predesign stage, design-associated professionals should consider items such as performing machine mockup and simulation studies, time line and link analyses, refined task analysis, and reviewing the analyses of the previous stage.

Finally, during the detailed design stage, design-associated professionals should consider items such as evaluating all critical man–machine mockups, performing link analyses for all important human–equipment interfaces, and developing function–flow schematic diagrams.

There are many advantages of considering human factors during the system design. Some of these are useful to reduce potential human errors, useful to increase productivity, useful to reduce difficulties in learning system operation and maintenance, useful to reduce the occurrence of accidents and injuries, useful to reduce equipment downtime, useful to reduce operator fatigue, useful to improve user acceptance, useful to reduce the cost of personnel training and selection, and useful to increase system safety [9, 19].

## 3.6  Human Factors Data Collection Sources, Data Documents, and Selective Data

In engineering designs, usually various types of human factors-related data are used, including body weights and dimensions, energy expenditure per grade of work, human error rates, and permissible noise exposure per unit time. There are many different forms in which such data may exist: design standards, mathematical functions and expressions, expert judgments, graphic representations, experience and common sense, quantitative data tables, *etc.* Nonetheless, six useful sources for collecting human factors-related data are as follows [6, 17]:

- **Published literature.** This includes journals, conference proceedings, technical reports, and books.
- **Published standards.** These documents are published by professional societies, government bodies, *etc.*
- **Previous experience.** These data are collected from similar cases that have occurred in the past.

- **Test reports.** These are basically the results form test performed on the manufactured items or goods.
- **User experience reports.** These are those reports that reflect experiences of the user community with the equipment in the field use environment.
- **Product development phase.** This is a quite useful source for obtaining a variety of human factors-related data.

Over the years, many good documents containing various types of human factors-related data have appeared. Ten of these are as follows [6]:

- Woodson, W.E., *Human Factors Design Handbook*, McGraw Hill Book Company, New York, 1972.
- White, R.M., The Anthropometry of United States Army Men and Women: 1946–1977, *Human Factors*, Vol. 21, 1979, pp. 473–482.
- Chapanis, A., *Human Factors in Systems Engineering*, John Wiley and Sons, New York, 1996.
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- *Anthropometry for Designers, Anthropometric Source Book 1*, Report No. 1024, National Aeronautics and Space Administration, Houston, Texas, 1978.
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- Phillips, C.A., *Human Factors Engineering*, John Wiley and Sons, New York, 2000.
- Van Cott, H.P., Kindade, R.G., Editors, *Human Engineering Guide to Equipment Design*, John Wiley and Sons, New York, 1972.

As mentioned earlier, there are many published sources for obtaining quantitative human factors-related data. Table 3.1 presents a sample of such data. The data presented in the table are concerned with body-related dimensions of the U.S. adult population (18–79 years) [8, 20, 21].

## 3.7  Useful Human Factors Guidelines for System Design

Over the years professionals working in the human factors area have developed many human factors-related guidelines for use in system design. Some of these guidelines are presented below [8, 22]:

**Table 3.1.** Some body dimension–related data values of the U.S. adult population (18–79 years)

| Data Description | 95th percentile (in inches) | | 5th percentile (in inches) | |
|---|---|---|---|---|
| | **Female** | **Male** | **Female** | **Male** |
| Weight | 199 (lb) | 217 (lb) | 104 (lb) | 126 (lb) |
| Standing height | 67.1 | 72.8 | 59 | 63.6 |
| Sitting height | 35.7 | 38 | 30.9 | 33.2 |
| Seated width | 17.1 | 15.9 | 12.3 | 12.2 |

- Prepare a human factors design checklist for use during system design and production cycle.
- Review system objectives from the human factors aspect.
- Acquire all applicable human factors design reference documents.
- Use appropriate mockups to "test" the effectiveness of user-hardware interface designs.
- Perform appropriate experiments when cited reference guides fail to provide satisfactory information for design related decisions.
- Review with care final production drawings in regard to human factors.
- Review thoroughly the entire initial design concept ideas.
- Use the services of human factors specialists as appropriate.
- Conduct appropriate field tests of the system design before approving it for delivery to customers.

## 3.8  Problems

1. Write an essay on the history of human factors.
2. Discuss human factors objectives.
3. Compare at least six man and machine characteristics.
4. List at least ten typical human behaviors.
5. Discuss the following human sensory-related capabilities:
   - Sight
   - Touch
   - Noise
6. Assume that a certain type of paper has a reflectance of 85%. Calculate the value of the brightness contrast, if the print on the paper has a reflectance of 8%.
7. What are the benefits of considering human factors during the system design?
8. Discuss at least four sources for obtaining human factors data.
9. Discuss considerations of human factors during four system design stages.
10. List at least seven useful human factors guidelines for system design.

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# 4

# Basic Human Reliability and Error Concepts

## 4.1 Introduction

Humans play a key role in the overall reliability of engineering systems because many such systems are interconnected by human links to a certain degree. Nowadays, their reliability and tendency to commit errors have become an important issue during the design of many engineering systems.

Although the terms "human reliability" and "human error" may mean basically the same thing to many people, in certain circumstances their distinction could be quite important. Nonetheless, their fundamental difference is clearly conveyed by their definitions. Human reliability is defined as the probability that a job or task will be completed successfully by an individual at any specified stage in system operation within a required minimum time (*i.e.*, if the time requirement exists) [1]. On the other hand, human error is defined as a failure to perform a given task (or the performance of a prohibited action), which could cause damage to equipment and property or disruption of scheduled operations [2].

The history of human reliability and error may be traced back to the late 1950s, when H.L. Williams pointed out that realistic system reliability analysis must include the human aspect as well [3, 4]. In 1960, A. Shapero et al. pointed out that human error is responsible for 20–50% of equipment failures [5]. In the 1960s, a number of publications, directly or indirectly, related to human reliability and error appeared in the form of journal and conference proceedings articles and technical reports [6].

In 1973, *IEEE Transactions on Reliability* published a special issue on human reliability [7]. In 1986, a book entitled *Human Reliability with Human Factors* appeared [4]. A large number of publications on human reliability/error are listed in References [8–11]. This chapter presents various introductory aspects of human reliability and error.

## 4.2 Occupational Stressors and Human Performance Effectiveness

Stress plays an important role in the reliability of an individual performing a certain task. There are basically the following four types of occupational stressors [4, 12].

- Occupational change-related stressors
- Occupational frustration-related stressors
- Workload-related stressors
- Miscellaneous stressors

The occupational change-related stressors are concerned with the occupational change that disrupts an individual's cognitive, behavioral, and physiological patterns of functioning. Some examples of the occupational change are relocation, promotion, and organizational restructuring. Normally, this type of stressors is present in an organization concerned with productivity and growth.

The occupational frustration–related stressors are concerned with problems of occupational frustration. This frustration is generated in situations where the job inhibits the meeting of stated goals or objectives. Some of the factors that form elements of occupational frustration are lack of effective communication, role ambiguity, ineffective career development guidance, and bureaucracy difficulties.

The workload-related stressors are concerned with the problems of work overload or work under-load. In the case of work overload, the job/task requirements exceed the ability of the concerned individual to satisfy them effectively. Similarly, in the case of work-under load the work activities being performed by the individual fail to provide sufficient stimulation. Three typical examples of the work under load are as follows [4, 12]:

- Repetitive performance
- Lack of any intellectual input
- Lack of proper opportunities to use individual's acquired skills and expertise

The miscellaneous stressors are all those stressors that are not included in the above three categories. Three examples of these stressors are noise, poor interpersonal relationships, and too much or too little lighting.

The relationship between human performance effectiveness and stress has been studied by various researchers over the years. They conclude that such relationship can be described by the curve shown in Figure 4.1 [2, 12]. The curve indicates that stress is not an entirely negative state. In fact, stress at a moderate level is necessary to increase human performance effectiveness to its optimal level. Otherwise, at very low stress, the task will be dull and not challenging, and in turn human performance effectiveness will not be at its maximum level.

On the other hand, stress beyond a moderate level will cause deterioration in human performance due to factors such as worry, fear, or other kinds of psychological stress. All in all, it may be concluded that when an individual is performing
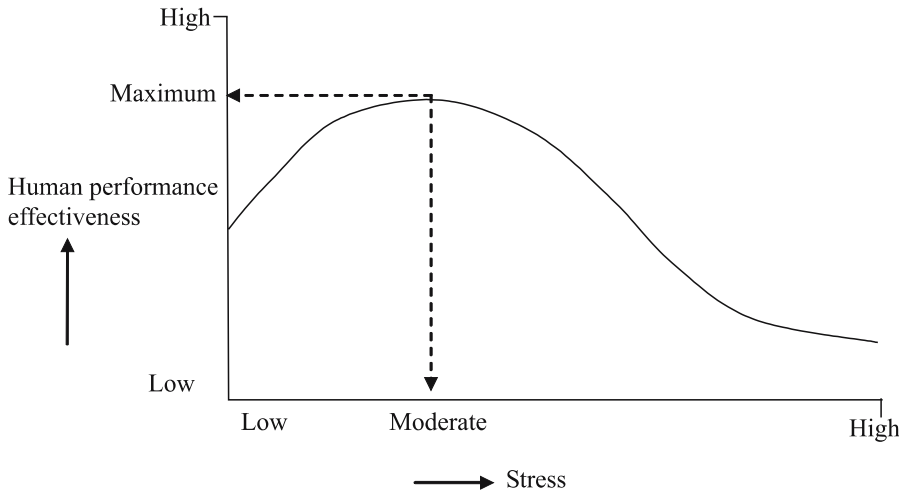
**Figure 4.1.** Human performance effectiveness versus stress curve

a task under high stress, the human error occurrence probability will be greater than when he/she is performing the same task under moderate stress.

# 4.3 Human Error Occurrence Reasons, Ways, and Consequences

Over the years, many different reasons for the occurrence of human errors have been identified [13–14]. Some of these reasons are follows [4, 13]:

- Poor training or skill
- Poor equipment design
- Complex task
- Poor work layout
- High temperature or noise level in the work area
- Distraction in the work area
- Poor lighting in the work area
- Poorly written equipment operating and maintenance procedures
- Improper work tools
- Poor verbal communication
- Poor motivation
- Crowded work space
- Poor management
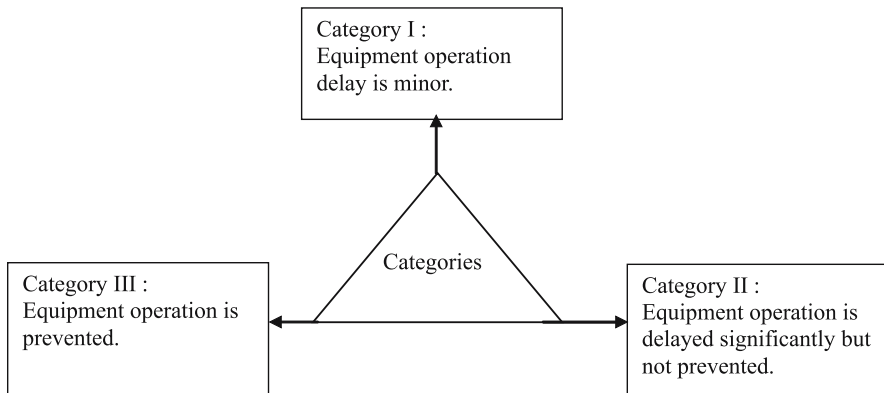
**Figure 4.2.** Categories of human error consequence with respect to equipment

There are many different ways for the occurrence of human error. Some of these are as follows [15]:

- **Way I:**   Failure to perform a required function
- **Way II:**  Taken wrong decision in responding to a difficulty
- **Way III:** Failure to realize a hazardous condition
- **Way IV:** Performing a task that should not have been executed
- **Way V:**   Poor timing and poor response to a contingency

There are various consequences of human error. They may vary form one task to another or one set of equipment to another. Furthermore, a consequence can range from minor to severe (*e.g.*, from a short delay in system performance to a major loss of property and lives). Nonetheless, in broad terms a human error consequence in regard to equipment may simply be classified under three categories as shown in Figure 4.2.

## 4.4  Human Error Classifications

Human errors may be classified under many categories. Meister [13] has classified human errors under the following seven categories:

- **Design Errors.** These errors occur due to inadequate designs. The three types of such errors are assigning inappropriate functions to humans, failure to implement human needs in the design, and failure to ensure the effectiveness of the man and machine interactions. An example of a design error is the placement of controls and displays so far apart that an operator finds difficulty in using both of them effectively.
- **Maintenance Errors.** These errors occur in the field environment normally due to incorrect repair or installation of the equipment. Two examples of maintenance

errors are incorrect calibration of equipment and the application of the wrong grease at appropriate points of the equipment.

- **Operator errors.** These errors usually occur in the equipment field-use environment due to operating personnel, when they fail to follow correct procedures, or there is lack of correct procedures. More specifically, some of the factors that can lead to operator errors are task complexity, operator carelessness, poor environmental conditions, poor training, lack of proper procedures, and departure from following the correct operating procedures.

- **Inspection errors.** These errors are associated with accepting out-of-tolerance items or rejecting in-tolerance items. According to various studies the inspection effectiveness average is around 85% [16].

- **Fabrication Errors.** These errors occur during product assembly because of poor workmanship. Some examples of these errors are using a wrong component, omitting a component, assembly incompatible with blueprints, part is wired backward, and wrong soldering. There could be a number of reasons for the occurrence of fabrication errors. Some of these are poor illumination, poor blueprints, excessive noise level, poorly designed work layout, and excessive temperature [6].

- **Handling errors.** These errors occur because of inappropriate transport or storage facilities, that are not in accordance with the manufacturer's recommendations.

- **Contributory errors.** These errors are the ones that are difficult to define either as human or related to equipment.

## 4.5  Human Performance Reliability Function

Humans perform various types of time continuous tasks including aircraft maneuvering, scope monitoring, and missile countdown. In conditions such as these, human performance reliability parameter plays an important role. The general human performance reliability function for time-continuous tasks can be developed in the same manner as the development of the general reliability function for hardware systems. Thus from Shooman [17], we write

$$E(t) = -\frac{1}{R_{hp}(t)} \cdot \frac{d\,R_{hp}(t)}{dt},$$
(4.1)

where

$E(t)$   is the time $t$ dependent error rate.

$R_{hp}(t)$ is the human performance reliability at time $t$.

Rearranging Equation (4.1) yields

$$-E(t)\,dt = \frac{d\,R_{hp}(t)}{R_{hp}(t)}.$$
(4.2)

By integrating both sides of Equation (4.2) over the time interval [0, $t$], we get

$$-\int_0^t E(t)\mathrm{d}t = \int_0^t \frac{1}{R_{hp}(t)} \cdot \mathrm{d}\,R_{hp}(t).$$ (4.3)

Since at $t=0$, $R_{hp}(t)=1$, we rewrite Equation (4.3) to the following form:

$$-\int_0^t E(t)\mathrm{d}t = \int_1^{R_{hp}(t)} \frac{1}{R_{hp}(t)} \cdot \mathrm{d}\,R_{hp}(t).$$ (4.4)

After evaluating the right hand side of Equation (4.4), we get

$$\ln R_{hp}(t) = -\int_0^t E(t)\,\mathrm{d}t.$$ (4.5)

Thus, from Equation (4.5), we get the following general expression for human performance reliability:

$$R_{hp}(t) = e^{-\int_0^t E(t)\,\mathrm{d}t}.$$ (4.6)

Equation (4.6) is the general expression for human performance reliability. Thus, it can be used to calculate human performance reliability for any time to human error statistical distribution including gamma, exponential, Weibull, and log-normal.

## 4.5.1  Experimental Justification for Some Time to Human Error Statistical Distributions

The United States Air Force (USAF) conducted an experiment to obtain human error data [18]. This experiment was concerned with an operator observing a clock-type light display and then requiring him/her to respond to a failed light event by pressing a hand-held switch. The results of this experiment indicated that the human error rate is a time variant (*i.e.*, nonconstant) and the experiment tested the three types of errors: times to miss error, times to false alarm error, and combined miss and false alarm error. Three probability density functions that emerged as the representative distributions for the goodness of fit to the error data were gamma, Weibull, and log-normal [18, 19].

**Example 4.1**
A transportation system operator's times to error are Weibull distributed, thus his/her time dependent error rate is expressed by:

$$E(t) = \frac{\beta}{\theta}\left(\frac{t}{\theta}\right)^{\beta-1},$$ (4.7)

where
$t$ is time.
$\beta$ is the shape parameter.
$\theta$ is the scale parameter.

Obtain the following:

(i) An expression for the operator's performance reliability function.
(ii) The operator's reliability for a 10-hour mission; if $\beta=1$ and $\theta=600$ hours.

By substituting Equation (4.7) into Equation (4.6) we get

$$R_{hp}(t) = e^{-\int_0^t \frac{\beta}{\theta}\left(\frac{t}{\theta}\right)^{\beta-1} dt},$$
$$= \exp\left[-\left(\frac{t}{\theta}\right)^{\beta}\right]. \tag{4.8}$$

Using the given data values in Equation (4.8) yields

$$R_{hp}(10) = \exp\left[-\left(\frac{10}{600}\right)\right],$$
$$= 0.9835.$$

Thus, the expression for the operator's performance reliability function is given by Equation (4.8) and his/her reliability is 0.9835.

## 4.5.2  Mean Time to Human Error

By integrating Equation (4.6) over the time interval $[0, \infty]$, we get

$$MTTHE = \int_0^\infty \left[ e^{-\int_0^t E(t)dt} \right] dt, \tag{4.9}$$

where
$MTTHE$ is the mean time to human error.

Equation (4.9) is the general expression for mean time to human error. More specifically, it can be used to compute mean time to human error for any time to human error statistical distribution (*e.g.*, exponential, Weibull, and gamma).

**Example 4.2**
A transportation system operator's times to human error are exponentially distributed, thus his or her error rate is 0.005 error/hour. Calculate the operator's mean time to human error.

Thus, we have

$$E(t) = 0.005 \text{ error/hour}$$

By substituting the above value into Equation (4.9), we get

$$MTTHE = \int_0^\infty e^{-\int_0^t (0.005)\, dt}\, dt,$$

$$= \int_0^\infty e^{-(0.005)\, t}\, dt,$$

$$= \frac{1}{0.005},$$

$$= 200 \text{ hours.}$$

Thus, the operator's mean time to human error is 200 hours.

## 4.6  Human Reliability and Error Analysis Methods

Over the years many human reliability and error analysis methods have appeared in the published literature [4]. Some of the basic ones are presented below and more general ones in Chapter 5.

### 4.6.1  Personnel Reliability Index Method

This index method was developed by the United States Navy for providing feedback on the technical proficiency of the electronic maintenance manpower [4, 20]. The index is based on nine job factors shown in Figure 4.3. There are various types of activities associated with each of these job factors. For example, activities associated with the electro-cognition factor are maintenance and troubleshooting of electronic equipment and the use of electronic maintenance reference materials.

The data are obtained from the maintenance supervisory staff over the period of two months for each of the job factors in Figure 4.3. These data are concerned with the number of uncommonly effective and uncommonly ineffective performances by individuals associated with maintenance activities. Using these data, the value of the following index, $R$, is calculated for each job factor:

$$R = \frac{\sum UEB}{\sum UEB + \sum UIB}, \qquad (4.10)$$

where
$UEB$ is the number of uncommonly effective behaviors.
$UIB$  is the number of uncommonly ineffective behaviors.

It is to be noted that the value of $R$ varies between zero and one. The overall effectiveness value, $E_0$, for a maintenance person is given by
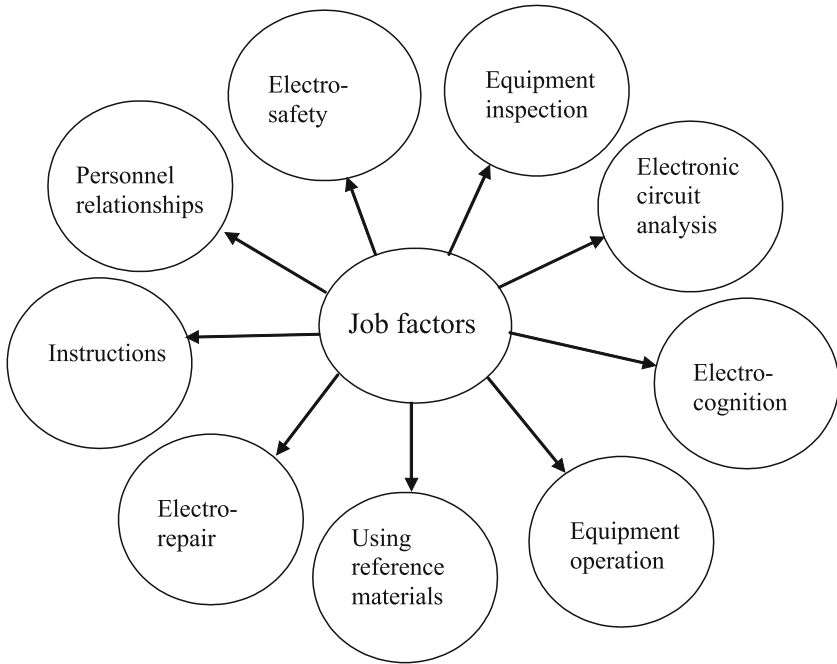
**Figure 4.3.** Job factors on which the personnel reliability index is based

$$E_0 = \prod_{i=1}^{9} R_i, \qquad (4.11)$$

where
$R_i$    is the index value (*i.e.*, reliability) of job factor *i*; for $i = 1, 2, 3, \ldots, 9$.

This index could be quite useful in areas such as design analysis and manpower training and selection.

### 4.6.2  Man–Machine Systems Analysis

The man–machine systems analysis (MMSA) method is concerned with reducing human error-caused unwanted effects to some acceptable level in a system. MMSA was developed in the early 1950s and is composed of the following steps [21]:

- **Step 1:**  Define system goals and its associated functions.
- **Step 2:**  Define all concerned situational characteristics (*i.e.*, the performance shaping factors such as air quality, illumination, and union actions under which individuals have to carry out their assigned tasks).
- **Step 3:**  Define characteristics (*e.g.*, skills, experience, motivation, and training) of all involved individuals.

- **Step 4:** Define jobs performed by all involved personnel.
- **Step 5:** Analyze all jobs in regard to identifying potential error-likely conditions and other related difficulties.
- **Step 6:** Estimate chances or other information in regard to the occurrence of all potential human errors.
- **Step 7:** Determine the likelihood that each potential human error will not be detected and rectified.
- **Step 8:** Determine all possible consequences, if potential human errors are not detected.
- **Step 9:** Recommend necessary changes.
- **Step 10:** Reevaluate each change by repeating most of the above steps.

### 4.6.3  Cause and Effect Diagram (CAED)

This method can be quite useful to perform human reliability and error analysis; it was developed in the early 1950s by K. Ishikawa [22]. Sometimes CAED is also referred to as the "Fishbone diagram" because of its resemblance to the skeleton of a fish. More specifically, the right-hand side of the CAED (*i.e.*, the fish head) represents effect, and the left hand-side represents all the possible causes that are connected to the central line known as the "Fish Spine." The following five main steps are used to develop a CAED [22]:

- Develop problem statement.
- Brainstorm to highlight all possible causes.
- Develop main cause categories by stratifying into natural groups and the steps of the process.
- Construct the diagram by linking all the highlighted causes under appropriate process steps and fill in the problem (*i.e.*, the effect) in the diagram box (*i.e.*, fish head).
- Refine cause classifications or categories by asking questions such as what causes this? And what is the exact reason for the existence of this condition?

There are many advantages of CAED including a useful tool to identify root causes, a useful tool to generate relevant ideas, a useful tool to present an orderly arrangement of theories, and a useful tool to guide further inquiry.

### 4.6.4  Error-cause Removal Program (ECRP)

This method was originally developed for reducing the occurrence of human errors to some tolerable level in production operations [23]. ECRP may simply be described as the production worker-participation program to reduce the occurrence of human errors. The emphasis of this method is on preventive measures rather than merely on remedial ones.

Some examples of the production workers are as follows [23]:

- Assembly personnel
- Machinists
- Inspection and maintenance personnel

Production workers are divided into teams with their own coordinators having appropriate technical and group-related skills. The maximum size of a team is restricted to twelve persons. Teams hold their meetings on a regular basis, in which workers present error and error-likely reports. The reports are reviewed and at the end recommendations are made for appropriate remedial measures. The team coordinators present the recommendations to management for its action.

It is to be noted that there are also various human factors and other specialists who assist both teams and management in regard to factors such as evaluation and implementation of the proposed design solutions. More specifically, ECRP is made up of the following basic elements [4]:

- All ECRP personnel are properly educated about the usefulness of the ECRP.
- Management recognizes the efforts of production workers in regard to ECRP.
- Management implements the most promising proposed design solutions.
- All concerned workers and coordinators are trained appropriately in data collection and analysis methods.
- Human factors and other specialist determine the effects of changes in the production process by considering the ECRP inputs.
- Production workers report and evaluate errors and error-likely conditions as well as they propose design solutions for eradicating error causes.
- Human factors and other specialist review proposed design solutions with respect to cost.

All in all, three useful guidelines concerning ECRP are as follows [11, 23]:

- Focus data collection to accident-prone conditions, error-likely conditions, and errors.
- Restrict to identifying those work conditions that require redesign to reduce the occurrence of error potential.
- Review each work redesign recommended by the team in regard to factors such as cost-effectiveness, the degree of error reduction, and increment in job satisfaction.

## 4.7 Problems

1. Discuss four types of occupational stressors.
2. Describe the human performance effectiveness versus stress curve.
3. List at least 12 reasons for the occurrence of human errors.
4. Discuss three categories of human error consequence with respect to equipment.

5.  Discuss the seven types of human errors.
6.  Compare design errors with operator errors.
7.  Obtain an expression for mean time to human error when time dependent error rate is represented by Equation (4.7).
8.  List the job factors on which the personnel reliability index is based.
9.  Describe the man–machine systems analysis (MMSA) method.
10. What are the seven basic elements of the error-cause removal program (ECRP)?

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# 5

# Methods for Performing Human Reliability and Error Analysis in Transportation Systems

## 5.1 Introduction

Over the years, a vast amount of literature on human factors, reliability, and safety has appeared in the form of journal articles, books, conference proceedings articles, and technical reports [1–4]. Many new methods and techniques have been developed in these three areas. Some of these methods and techniques are being applied successfully across many diverse areas such as engineering design, health care, management, and maintenance. Three examples of these methods and techniques are failure modes and effect analysis (FMEA), the Markov method, and fault tree analysis (FTA). FMEA was developed in the early 1950s to analyze engineering systems from the reliability aspect. Today, it is being used across many diverse areas including health care and transportation.

The Markov method is a highly mathematical approach often used to perform various types of reliability and safety analyses in engineering systems. Nowadays, it is also being used in areas such as maintenance, transportation, and health care. Finally, the FTA approach was developed in the early 1960s to perform safety analysis of rocket launch control systems. Today, it is being used across many diverse areas such as nuclear power generation, aerospace, health care, and management.

This chapter presents a number of methods and techniques considered useful to perform human reliability and error analysis in transportation systems, extracted from the published literature on reliability, safety, and human factors.

## 5.2 Probability Tree Method

The probability tree method is frequently used to perform task analysis in the technique for the human error rate prediction (THERP) [5]. In performing task analysis, the method diagrammatically denotes critical human actions and other related

events. More specifically, diagrammatic task analysis is represented by the branches of the probability tree. The branching limbs represent outcomes (*i.e.*, success or failure) of each event associated with a given problem and each branch is assigned an occurrence probability.

Some of the advantages of this method are an effective visibility tool, simplified mathematical computations, and a useful tool to predict the quantitative effects of errors. In addition, this method can incorporate, with some modifications, factors such as interaction stress, emotional stress, and interaction effects [1]. Additional information on the method is available in Reference [5]. The following example demonstrates the application of the probability tree method to a human reliability-related transportation system problem.

**Example 5.1**

A transportation system operator performs three independent tasks: *x*, *y*, and *z*. Task *x* is performed before task *y*, and task *y* before task *z*. Each of these three tasks can be performed either correctly or incorrectly. Develop a probability tree for the example and obtain an expression for the probability of not successfully accomplishing the overall mission by the operator.

In this case, the transportation system operator first performs task *x* correctly or incorrectly and then proceeds to carry out task *y*. Task *y* can also be performed either correctly or incorrectly by the operator. Finally, the operator performs task *z* with two outcomes: correct and incorrect. This entire scenario is depicted by a probability tree shown in Figure 5.1.

The six symbols used in Figure 5.1 are defined below.

*x*   represents the event that task *x* is performed correctly.
$\overline{x}$   represents the event that task *x* is performed incorrectly.
*y*   represents the event that task *y* is performed correctly.
$\overline{y}$   represents the event that task *y* is performed incorrectly.
*z*   represents the event that task *z* is performed correctly.
$\overline{z}$   represents the event that task *z* is performed incorrectly.

By examining the diagram in Figure 5.1, it can be noted that there are seven distinct possibilities, $\left( \text{i.e., } x\,y\,\overline{z}, x\,\overline{y}\,z, x\,\overline{y}\,\overline{z}, \overline{x}\,y\,z, \overline{x}\,y\,\overline{z}, \overline{x}\,\overline{y}\,z, \text{ and } \overline{x}\,\overline{y}\,\overline{z} \right)$ for having an overall mission failure. Thus, the probability of not successfully accomplishing the overall mission by the transportation operator is

$$P_{\text{tso}} = P\left( x\,y\,\overline{z} + x\,\overline{y}\,z + x\,\overline{y}\,\overline{z} + \overline{x}\,y\,z + \overline{x}\,y\,\overline{z} + \overline{x}\,\overline{y}\,z + \overline{x}\,\overline{y}\,\overline{z} \right),$$

$$= P_x P_y P_{\overline{z}} + P_x P_{\overline{y}} P_z + P_x P_{\overline{y}} P_{\overline{z}} + P_{\overline{x}} P_y P_z + P_{\overline{x}} P_y P_{\overline{z}} + P_{\overline{x}} P_{\overline{y}} P_z + P_{\overline{x}} P_{\overline{y}} P_{\overline{z}},$$

(5.1)

where
$P_{\text{tso}}$   is the probability of not successfully accomplishing the overall mission by the transportation system operator.
$P_x$   is the probability of performing task *x* correctly.
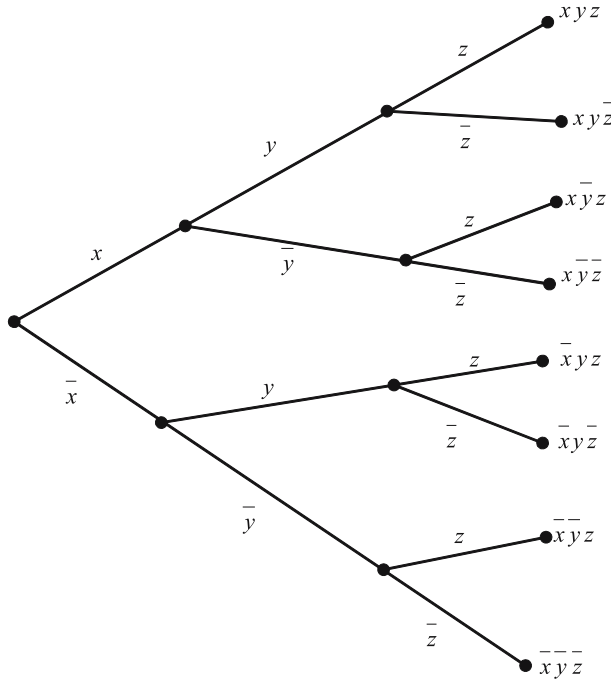
**Figure 5.1.** Probability tree for the transportation system operator performing tasks $x, y,$ and $z$

$P_{\bar{x}}$    is the probability of performing task $x$ incorrectly.

$P_y$    is the probability of performing task $y$ correctly.

$P_{\bar{y}}$    is the probability of performing task $y$ incorrectly.

$P_z$    is the probability of performing task $z$ correctly.

$P_{\bar{z}}$    is the probability of performing task $z$ incorrectly.

Since $P_{\bar{x}} = 1 - P_x$, $P_{\bar{y}} = 1 - P_y$, and $P_{\bar{z}} = 1 - P_z$, Equation (5.1) reduces to

$$P_{tso} = P_x P_y \left(1 - P_z\right) + P_x P_z \left(1 - P_y\right) + P_x \left(1 - P_y\right)\left(1 - P_z\right)$$
$$+ P_y P_z \left(1 - P_x\right) + P_y \left(1 - P_x\right)\left(1 - P_z\right) + P_z \left(1 - P_x\right)\left(1 - P_y\right) + \left(1 - P_x\right)\left(1 - P_y\right)\left(1 - P_z\right),$$
$$= 1 - P_x P_y P_z .$$

$$(5.2)$$

**Example 5.2**

Assume that in Example 5.1, the probabilities of the transportation system operator performing tasks $x$, $y$, and $z$ incorrectly are 0.1, 0.2, and 0.3, respectively. Calculate the probability of not successfully accomplishing the overall mission by the operator.

Thus, we have

$$Px = 1 - 0.1 = 0.9,$$
$$Py = 1 - 0.2 = 0.8,$$
$$Pz = 1 - 0.3 = 0.7.$$

By substituting the above values into Equation (5.2), we get

$$P_{tso} = 1 - (0.9)(0.8)(0.7),$$
$$= 0.496.$$

Thus, the probability of not successfully accomplishing the overall mission by the transportation system operator is 0.496.

## 5.3 Failure Modes and Effect Analysis (FMEA)

Failure Mode and Effect Analysis is probably the most widely used method in the industrial sector to analyze engineering systems from the reliability aspect. FMEA may simply be described as an effective approach for performing analysis of each potential failure mode in a given system to determine the effects of such failure modes on the total system [6]. This method is called failure mode effects and critical analysis (FMECA) when the effect of each failure mode is classified according to its severity.

FMEA was developed in the early 1950s by the United States Navy's Bureau of Aeronautics and it was called "Failure Analysis" [7]. Subsequently, it was renamed to "Failure Effect Analysis," and the Bureau of Naval Weapons (the successor to the Bureau of Aeronautics) introduced it into its new specification on flight controls [8]. The United States National Aeronautics and Astronautics Administration (NASA) extended the functions of the FMEA and called it FMECA [9]. The method is described in detail in References [10, 11], and a comprehensive list of publications on FMEA is available in Reference [12].

### 5.3.1 Steps for Performing FMEA

FMEA is performed by following a number of steps. Seven main steps concerned with performing FMEA are shown in Figure 5.2 [2, 11].

Define system boundaries and its associated requirements in detail

List all system parts and subsystems

Identify and describe each component and list its all failure modes

Assign appropriate failure rates or probabilities to each component failure mode

List effect or effects of each failure mode on subsystem, system, and plant

Enter remarks for all failure modes

Review all critical failure modes and take appropriate measures

**Figure 5.2.** Seven main steps for performing FMEA

### 5.3.2  FMEA Benefits

There are many benefits of performing FMEA. Some of these are as follows [10, 11]:

- Useful to identify safety concerns to be focused on
- A visibility tool for management
- A systematic method for classifying hardware failures
- Easy to understand
- Useful to improve communication among design interface personnel
- Useful to reduce engineering changes
- Useful to provide safeguard against repeating the same mistakes in the future
- Useful to reduce development time and cost
- A useful approach that begins from the detailed level and works upward
- Useful to improve customer satisfaction

## 5.4  Technics of Operation Review (TOR)

The Technics of Operation Review) method was developed in the early 1970s, and it may simply be described as a hands-on analytical methodology for identifying the root system causes of an operation failure [13]. The method uses a worksheet containing simple terms requiring "yes/no" decisions and is activated by an incident occurring at a specific location and time involving certain individuals.

The following steps are associated with the TOR method [14]:

- Form the TOR team by ensuring that its members represent all concerned areas.
- Impart common knowledge to all team members by holding a roundtable session.
- Highlight a key systemic factor that was instrumental in causing the incident/ accident to occur. Ensure that this factor is based on the team consensus and serves as a starting point for further investigation.
- Use the team consensus in responding to a sequence of "yes/no" options.
- Evaluate all the identified factors and ensure the existence of the team consensus in regard to the evaluation of each of these factors.
- Prioritize the contributory factors and start the process with the most serious factor.
- Establish appropriate preventive/corrective strategies for each contributory factor.
- Implement strategies.

Finally, it is to be noted that the main strength of the TOR approach is the involvement of line personnel in the analysis, and its main weakness: It is an after-the-fact process.

## 5.5  The Throughput Ratio Method

The throughput ratio method is a reliability-oriented predictive method that was developed by the United States Navy Electronics Laboratory Center [15]. The throughput ratio determines the operability of man–machine interfaces or stations such as control panels. The term "operability" may be defined as the extent to which the man–machine station performance satisfies the design expectation for a given station [1, 15]. Furthermore, the term "throughput" implies transmission, because the ratio is expressed in terms of responses or items per unit time emitted by the human operator.

The actual throughput ratio in percentage is expressed by [1, 15]:

$$MMO = \left[ \frac{\theta}{\gamma} - CF \right](100), \tag{5.3}$$

where

$MMO$   is the man–machine operability expressed in percentage.

$\gamma$   is the number of throughput items to be generated per unit time to satisfy design expectation.

$\theta$   is the number of throughput items generated per unit time.

$CF$   is the correction factor (*i.e.*, correction for error or out-of-tolerance output).

In turn, the correction factor, $CF$, is defined by

$$CF = \left[ \frac{n_1}{n_2} \cdot \frac{\theta}{\gamma} \right]^2 P_f\, P_{fd}^2, \tag{5.4}$$

where

$n_2$   is the number of trials in which the control-display operation is performed.

$n_1$   is the number of trials in which the control-display operation is conducted incorrectly.

$P_f$   is the probability of function failure because of a human error.

$P_{fd}$   is the probability that the human operator will fail to detect error.

Some of the areas in which the throughput ratio method can be used are to demonstrate system acceptability, to compare alternative design operability, and to establish system feasibility [1, 15].

**Example 5.3**

Calculate the value of the throughput ratio, if the values of $P_f$, $P_{fd}$, $n_1$, $n_2$, $\theta$, and $\gamma$ are 0.7, 0.2, 2, 10, 5, and 11, respectively.

By substituting the given data values into Equation (5.4), we get

$$CF = \left[ \frac{2}{10} \cdot \frac{5}{11} \right]^2 (0.7)(0.2),$$
$$= 0.0011.$$

Inserting the above calculated value and the given data values into Equation (5.3) yields

$$MMO = \left[ \frac{5}{11} - 0.0011 \right] (100),$$
$$= 45.34\%.$$

Thus, the value of the throughput ratio (*i.e.*, man–machine operability) is 45.34%.

## 5.6  Fault Tree Analysis

Fault tree analysis is a widely used method in the industrial sector to perform reliability analysis of engineering systems. It was developed in the early 1960s at the Bell Telephone Laboratories to perform safety analysis of the Minuteman launch control system [2].

A fault tree may simply be described as a logical representation of the relationship of basic fault events that may cause a specified undesirable event, called the "top event," to occur. It is depicted (*i.e.*, fault tree) using a tree structure with logic gates such as OR and AND.

There is probably nothing basically new about the principle used for the generation of fault trees. It consists of successively asking the question "What are the possible ways for this fault event to occur?". However, the newness lies in the use of logic gates or operators in the organization and graphical representation of the logic structure relating the top event to basic fault events.

### 5.6.1  Fault Tree Symbols

Although, there are many symbols used in the construction of fault trees, the four basic ones are shown in Figure 5.3 [2, 16]. Other symbols are described in References [2, 11, 16, 17]. Each of the symbols in Figure 5.3 is described below.

- **OR gate.** This gate denotes that an output fault event will occur if any one or more of its input fault events occur.
- **AND gate.** This gate denotes that an output fault event will occur only if all of its input fault events occur.
- **Circle.** It denotes a basic fault event or the failure of an elementary part or a component.
- **Rectangle.** It denotes a fault event which results from the logical combination of fault events through the input of a logic gate.
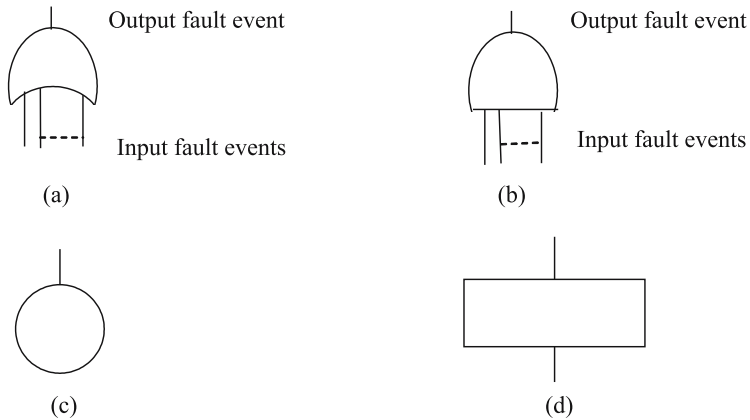
**Figure 5.3.** Four basic symbols used in the fault tree construction: (**a**) OR gate, (**b**) AND gate, (**c**) Circle, (**d**) Rectangle

## 5.6.2 Steps for Performing Fault Tree Analysis

Normally, the following seven steps are used to perform fault tree analysis (FTA) [18]:

- Define the system and the assumptions pertaining to it.
- Identify the system top fault event (*i.e.*, the system undesirable event to be investigated).
- Identify all the possible causes that can cause the top event to occur, by using fault tree symbols and the logic tree format.
- Develop the fault tree to the lowest detail level as per the requirements.
- Perform analysis of the completed fault tree in regard to factors such as understanding the proper logic and the interrelationships among various fault paths and gaining proper insight into the unique modes of product/item faults.
- Identify most appropriate corrective measures.
- Document the analysis with care and follow up on the identified corrective measures.

**Example 5.4**
A windowless room has a switch that can only fail to close and two light bulbs. Develop a fault tree for the undesired event (*i.e.*, top event): a dark room.

Thus, in this case the room can only be dark if there is no electricity, the switch fails to close, or both the light bulbs burn out.

By using the symbols in Figure 5.3, the fault tree shown in Figure 5.4 for this example was developed. Each fault event in the fault tree diagram is labelled as $E_1$, $E_2$, $E_3$, $E_4$, $E_5$, $E_6$, $E_7$, and $E_8$.
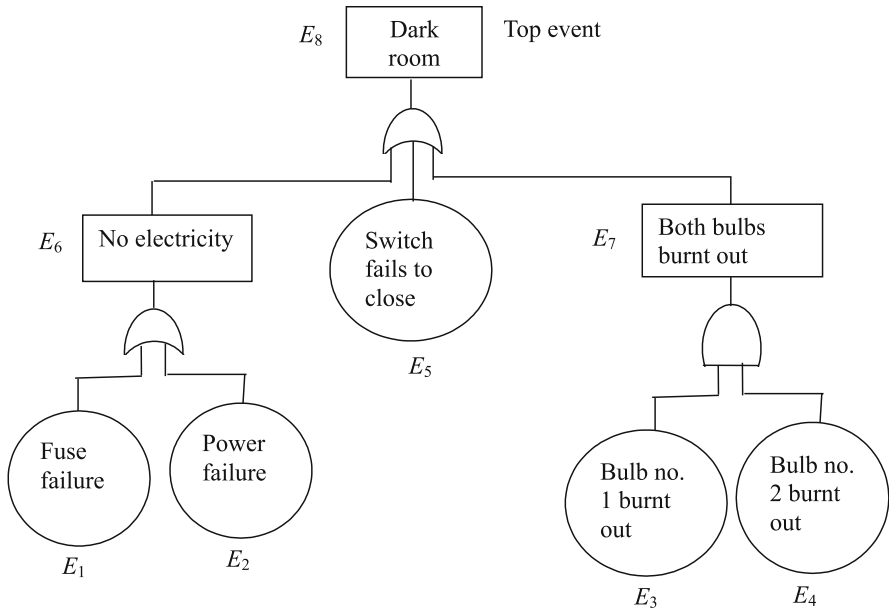
**Figure 5.4.** Fault tree for the top or undesired event: dark room

## 5.6.3  Probability Evaluation of Fault Trees

The occurrence probability of the top event of a fault tree can be calculated when the probabilities of the occurrence of basic fault events are known. This can only be obtained by first calculating the occurrence probability of the resultant (*i.e.*, output) fault events of intermediate and lower logic gates such as AND and OR. Thus, the probability of occurrence of the AND gate output fault event is expressed by [11]:

$$P(x_0)=\prod_{i=1}^{n} P(x_i),\qquad (5.5)$$

where
$P(x_0)$ is the probability of occurrence of the AND gate output fault event, $x_0$.
$n$      the number of AND gate input fault events.
$P(x_i)$ is the occurrence probability of AND gate input fault event $x_i$; for $i=1, 2, 3, …, n$.

Similarly, the probability of occurrence of the OR gate output fault event is given by [11]

$$P(y_0)=1-\prod_{i=1}^{k}\{1-P(y_i)\},\qquad (5.6)$$

where
$P(y_o)$ is the probability of occurrence of the OR gate output fault event, $y_o$.
$k$       the number of OR gate input fault events.
$P(y_i)$ is the occurrence probability of OR gate input fault event $y_i$; for $i = 1, 2, 3, …, k$.

**Example 5.5**
Assume that in Figure 5.4 the probabilities of occurrence of events $E_1$, $E_2$, $E_3$, $E_4$, and $E_5$ are 0.04, 0.02, 0.08, 0.08, and 0.07, respectively. Calculate the probability of occurrence of the undesired event (*i.e.*, the top event): dark room.

By inserting the specified data values into Equation (5.5), we get the following probability value, for the occurrence of event both bulbs burnt out, $E_7$:

$$P(E_7) = P(E_3) P(E_4),$$
$$= (0.08)(0.08),$$
$$= 0.0064.$$

Similarly, by substituting the given data values into Equation (5.6), we get the following probability value, for the occurrence of event no electricity, $E_6$:

$$P(E_6) = 1 - \{1 - P(E_1)\} \{1 - P(E_2)\},$$
$$= 1 - \{1 - 0.04\} \{1 - 0.02\},$$
$$= 1 - (0.96)(0.98),$$
$$= 0.0592.$$

By substituting the above two calculated values and the given data value into Equation (5.6), we get the following probability value for the occurrence of the top event, dark room:

$$P(E_8) = 1 - \{1 - P(E_6)\} \{1 - P(E_5)\}\{1 - P(E_7)\},$$
$$= 1 - (1 - 0.0592)(1 - 0.07)(1 - 0.0064),$$
$$= 0.1307.$$

Thus, the probability of occurrence of the undesired event: dark room is 0.1307.

## 5.7  Pareto Analysis

The Pareto method is used to separate the most important causes of a given problem from the trivial ones; it is named after Vilfredo Pareto (1848–1923), an Italian economist. In human reliability and error analysis, it can be quite useful to identify areas for a concerted effort. The method is composed of the following steps [11, 19]:

- Prepare a list of causes in a tabular form and count their occurrences.
- Arrange all these causes in descending order.
- Calculate the total for the complete list.
- Calculate the percentage of the total for each cause.
- Construct a Pareto diagram that shows percentages vertically and their corresponding causes horizontally.
- Draw appropriate conclusions from the end results.

## 5.8  Pontecorvo Method

The Pontecorvo method is used to obtain reliability estimates of task performance by an individual [20]. The method first obtains estimates of reliability for separate and discrete subtasks having no correct reliability figures, and then it obtains the total task reliability by combining these estimates. Normally, Pontecorvo method is used during the initial phases of design and is composed of the following six steps [1, 20]:

- **Identify tasks.** This step is concerned with identifying the tasks to be performed. These tasks are identified at a gross level. More specifically, each task denotes one complete operation.
- **Identify all the subtasks associated with each task** (*i.e.*, those subtasks that are essential for task completion).
- **Collect relevant empirical performance data.** These data are obtained from various sources including experimental literature and in-house operations.
- **Establish subtask rate.** This is established by rating each subtask according to its level of difficulty or potential for error. Usually, a 10-point scale that varies from least error to most error, is used to judge the subtask rate.
- **Predict subtask reliability.** This is accomplished by expressing the judged ratings of the data and the empirical data in the form of a straight line and then testing the regression line for goodness of fit.
- **Determine task reliability.** The task reliability is obtained by multiplying subtask reliabilities.

The above approach is employed to estimate the performance of a single person acting alone. However, when a backup person is available, the probability for the task being performed correctly increases. Although, this is very true, the backup person may not be available all of the time. In this situation, the overall reliability of two persons working independently together to accomplish a task can be calculated by using the following equation [20]:

$$R_{OV} = \left[ \left\{ 1 - \left( 1 - R_{sp} \right)^2 \right\} T_a + R_{sp} \, T_u \right] \Big/ \left( T_a + T_u \right), \tag{5.7}$$

where

$R_{sp}$    is single person reliability.
$T_a$    is the percentage of time the backup person is available.
$T_u$    is the percentage of time the backup person is unavailable.

**Example 5.6**

Assume that two persons work independently to perform maintenance on a transportation system. The reliability of each person is 0.8, and only 60% of time is the backup person available. Compute the reliability of carrying out the maintenance task correctly.

Thus, the percentage of time the backup person unavailable is given by

$$T_u = 1 - 0.6,$$
$$= 0.4 \ or \ 40\%.$$

By substituting the above calculated value and the specified data values into Equation (5.7), we get

$$R_{OV} = \left[\left\{1 - \left(1 - 0.8\right)^2\right\}0.6 + (0.8)(0.4)\right]\Big/(0.6 + 0.4),$$
$$= 0.896.$$

Thus, the reliability of performing the maintenance task correctly is 0.896.

## 5.9  Markov Method

The Markov method, named for Andrei Andreyevich Markov (1856–1922), a Russian mathematician, is widely used to perform various types of reliability studies in the industrial sector. In the past, the Markov method has also been used in performing human reliability analysis [1]. Thus, it could be a quite useful tool to conduct various types of human reliability and error analysis in transportation systems.

The Markov method is subject to the following assumptions [21]:

- All occurrences are independent.
- The probability of the occurrence of a transition from one system state to another in the finite time interval $\Delta t$ is given by $\lambda \Delta t$, where $\lambda$ is the constant transition rate from one system state to another.
- The probability of more than one occurrences in the finite time interval $\Delta t$ from one system state to another is negligible (*e.g.*, $(\lambda \Delta t)(\lambda \Delta t) \rightarrow 0$).

The application of the Markov method in performing human reliability analysis is demonstrated through the following example:

## Example 5.7

Assume that an airline pilot makes errors at a constant rate, $\lambda$. This scenario is described in more detail by the state space diagram shown in Figure 5.5. The numerals in the diagram denote system states. Develop expressions for the pilot's reliability at time $t$ and mean time to human error by using the Markov method.
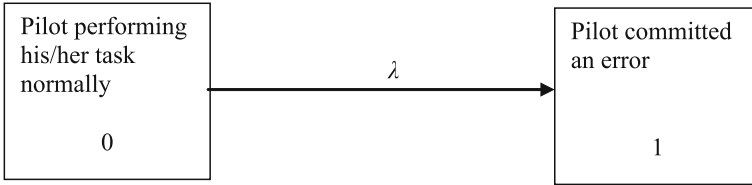


**Figure 5.5.** State space diagram representing the pilot

By using the Markov method, we write down the following equations for the diagram in Figure 5.5 [11, 21]:

$$P_0(t+\Delta t) = P_0(t)(1-\lambda \Delta t), \tag{5.8}$$

$$P_1(t+\Delta t) = P_0(t) \lambda \Delta t + P_1(t), \tag{5.9}$$

where
$P_0(t+\Delta t)$  is the probability that the pilot is performing his/her task normally or correctly at time $(t+\Delta t)$.
$P_0(t)$       is the probability that the pilot is performing his/her task normally at time t.
$\lambda$       is the constant error rate of the pilot.
$\lambda \Delta t$     is the probability of human error by the pilot in finite time interval $\Delta t$.
$(1-\lambda \Delta t)$   is the probability of no error by the pilot in finite time interval $\Delta t$
$P_1(t)$       is the probability that the pilot has committed an error at time $t$
$P_1(t+\Delta t)$  is the probability that the pilot has committed an error at time $t+\Delta t$.

By rearranging Equations (5.8)–(5.9) and taking the limit as $\Delta t \to 0$, we get

$$\lim_{\Delta t \to 0} \frac{P_0(t+\Delta t)-P_0(t)}{\Delta t} = \frac{d P_0(t)}{dt} = -\lambda P_0(t), \tag{5.10}$$

and

$$\lim_{\Delta t \to 0} \frac{P_1(t+\Delta t)-P_1(t)}{\Delta t} = \frac{d P_1(t)}{dt} = \lambda P_0(t). \tag{5.11}$$

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

Solving Equations (5.10)–(5.11) by using Laplace transforms, we get

$$P_0(s) = \frac{1}{s+\lambda},$$ (5.12)

and

$$P_1(s) = \frac{\lambda}{s(s+\lambda)},$$ (5.13)

where
$s$ is the Laplace transform variable.

Taking the inverse Laplace transforms of Equations (5.12)–(5.13), we obtain

$$P_0(t) = e^{-\lambda t},$$ (5.14)

$$P_1(t) = \left(1 - e^{-\lambda t}\right).$$ (5.15)

Thus, the pilot's reliability, $R_p(t)$, at time $t$ is given by

$$R_p(t) = P_0(t) = e^{-\lambda t}.$$ (5.16)

The pilot's mean time to human error, $MTTHE_p$, is given by

$$MTTHE_p = \int_0^\infty R_p(t)\,dt,$$

$$= \int_0^\infty e^{-\lambda t}\,dt,$$ (5.17)

$$= \frac{1}{\lambda}.$$

### Example 5.8

Assume that a pilot's constant error rate is 0.0004 errors/hour. Calculate the pilot's reliability for a 10-hour mission and mean time to human error.

By substituting the given data values into Equations (5.16) and (5.17), we get

$$R_p(10) = e^{-(0.0004)\,(10)},$$
$$= 0.9960,$$

and

$$MTTHE_p = \frac{1}{0.0004},$$
$$= 2,500 \text{ hours.}$$

Thus, the pilot's reliability and mean time to human error are 0.9960 and 2,500 hours, respectively.

## 5.10  Block Diagram Method

The block diagram method can be used to calculate reliability of a m unit parallel system with human errors. Human errors are classified under two categories: critical and noncritical human errors. A critical human error causes system failure, whereas a noncritical human error results in only a single unit failure. A block diagram representing the above situation is shown in Figure 5.6. In this figure hypothetical blocks representing critical and noncritical human errors are placed in series with system and units, respectively.
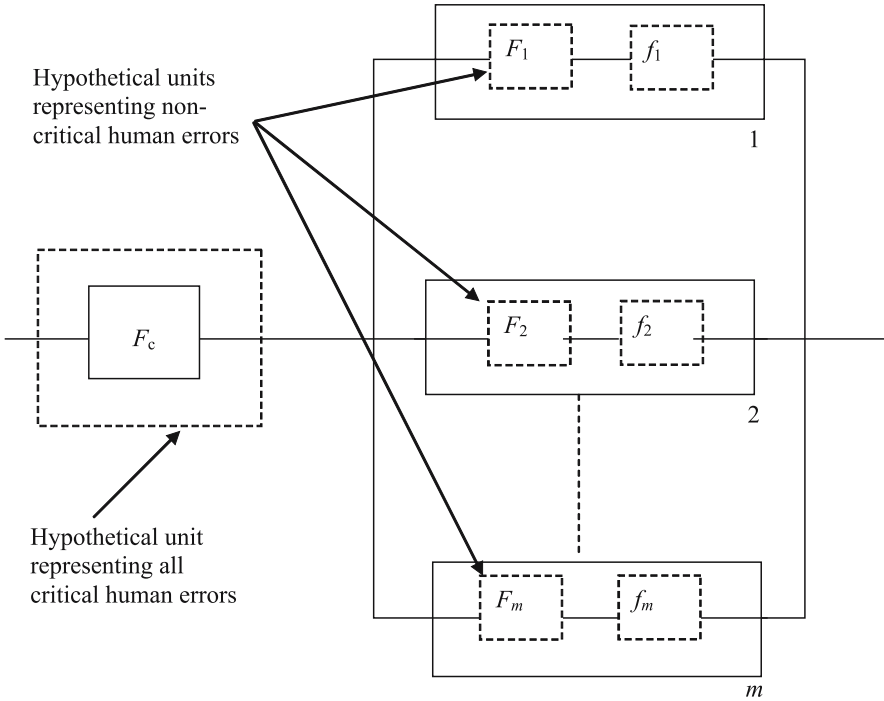


**Figure 5.6.** Block diagram of a parallel system with critical and noncritical human errors

The method assumes that each unit's failure probabilities can be separated into probabilities of hardware failures (*i.e.*, non-human error failures) and human errors, as well as it is possible to estimate the probability of the total system failure due to human errors.

The reliability of the parallel system shown in Figure 5.6 is given by [11]:

$$R_{ps} = \left[ 1 - \prod_{i=1}^{m} \left\{ 1 - (1 - f_i)(1 - F_i) \right\} \right] (1 - F_c),$$

$(5.18)$

where

$R_{ps}$   is the parallel system reliability.

$m$   is the number of active units in parallel.

$F_c$   is the failure probability of the parallel system due to critical human errors.

$f_i$   is the hardware failure (*i.e.*, non human error failure) probability of unit $i$; for $i = 1, 2, 3, …, m$.

$F_i$   is the failure probability of unit $i$ due to non-critical human errors; for $i = 1, 2, 3, …, m$.

For constant hardware failure and critical and noncritical human error rates, the time $t$ dependent equations for $F_c$, $F_i$, and $f_i$ are [1, 11]:

$$F_c(t) = 1 - e^{-\lambda_c t}, \tag{5.19}$$

$$F_i(t) = 1 - e^{-\lambda_{nci} t}, \tag{5.20}$$

and

$$f_i(t) = 1 - e^{-\lambda_i t}, \tag{5.21}$$

where

$F_c(t)$   is the failure probability of the parallel system due to critical human error at time $t$.

$f_i(t)$   is the hardware failure probability of unit $i$ at time $t$; for $i = 1, 2, 3, …, m$.

$F_i(t)$   is the failure probability of unit $i$ due to noncritical human error at time $t$; for $i = 1, 2, 3, …, m$.

$\lambda_c$   is the system constant critical human error rate.

$\lambda_{nci}$   is the constant non-critical human error rate of unit $i$; for $i = 1, 2, 3, …, m$.

$\lambda_i$   is the constant hardware failure rate of unit $i$; for $i = 1, 2, 3, …, m$.

Substituting Equations (5.19)–(5.21) into Equation (5.18), yields

$$R_{ps}(t) = \left[ 1 - \prod_{i=1}^{m} \left\{ 1 - e^{-\lambda_i t} e^{-\lambda_{nci} t} \right\} \right] e^{-\lambda_c t}, \tag{5.22}$$

where

$R_{ps}(t)$ is the parallel system reliability at time $t$.

For identical units, Equation (5.22) becomes

$$R_{ps}(t) = \left[ 1 - \left( 1 - e^{-(\lambda + \lambda_{nc})t} \right)^m \right] e^{-\lambda_c t}, \tag{5.23}$$

where

$\lambda$   is the unit constant hardware failure rate.

$\lambda_{nc}$   is the unit constant noncritical human error rate.

The parallel system mean time to failure ($MTTF_{ps}$) is given by [1, 11]:

$$MTTF_{ps} = \int_0^{\infty} R_{ps}(t) \, dt. \tag{5.24}$$

Thus, inserting Equation (5.23) into Equation (5.24) yields

$$MTTF_{ps} = \frac{1}{\lambda_c} - \sum_{i=0}^{m} \binom{m}{i} (-1)^{m-i} \frac{1}{(m-1)(\lambda + \lambda_{nc}) + \lambda_c},$$    (5.25)

where

$$\binom{m}{i} = \frac{m!}{i!(m-i)!}.$$    (5.26)

In similar manner equations for other configurations can be developed [2].

**Example 5.9**

Assume that a two independent and identical unit parallel system, used in a transportation system, can fail either due to critical human errors or when all its units fail due to hardware failures or non-critical human errors. The constant hardware failure, critical human error, and noncritical human error rates are 0.0009 failures/hour, 0.0001 errors/hour, and 0.0003 errors/hour, respectively.

Calculate the system reliability for a 100-hour mission and mean time to failure.

By substituting the given data values into Equation (5.23), we get

$$R_{ps}(100) = \left[ 1 - \left( 1 - e^{-(0.0009 + 0.0003)(100)} \right)^2 \right] e^{-(0.0001)(100)},$$

$$= 0.9774.$$

Similarly, substituting the specified data values into Equation (5.25) yields

$$MTTF_p = \frac{2}{\lambda + \lambda_{nc} + \lambda_c} - \frac{1}{2\lambda + 2\lambda_{nc} + \lambda_c},$$

$$= \frac{2}{(0.0009 + 0.0003 + 0.0001)} - \frac{2}{(2(0.0009) + 2(0.0003) + 0.0001)},$$

$$= 1138.46 \text{ hours.}$$

Thus, the system reliability and mean time to failure are 0.9774 and 1138.46 hours, respectively.

# 5.11  Problems

1. A transportation system operator performs two independent tasks: a and b. Task a is performed before task b, and both the tasks can be performed either correctly or incorrectly. Develop a probability tree and obtain an expression for the probability of not successfully accomplishing the overall mission by the operator.
2. Write an essay on the historical developments concerning failure modes and effect analysis (FMEA).
3. What are the benefits of performing FMEA?

4. What is the difference between FMEA and failure mode effects and criticality analysis (FMECA)?

5. Describe the technics of operation review) method in regard to its application in performing human error analysis in transportation systems.

6. Describe the following symbols/terms used in fault tree analysis (FTA):
   - OR gate
   - AND gate
   - Resultant event
   - Circle

7. Compare FTA with FMEA.

8. Assume that a windowless room has a switch that can only fail to close and four light bulbs. Develop a fault tree for the top event: dark room.

9. Discuss Pareto analysis in regard to its application in performing human error analysis in transportation systems.

10. Describe the six steps associated with the Pontecorvo method.

11. Assume that a three independent and identical unit parallel system, used in a transportation system, can fail either due to critical human errors or when all its units fail due to hardware failures or noncritical human errors. The constant hardware failure, critical human error, and noncritical human error rates are 0.0008 failures/hour, 0.0002 errors/hour, and 0.0004 errors/hour, respectively. Calculate the system mean time to failure.

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# 6

# Human Error in Railways

## 6.1  Introduction

The railway system is still an important means of transportation around the world. Each day it transports millions of dollars worth of goods and millions of passengers from one end to another. In the United States, the railway system is composed of roughly 3000 stations and track terminals that serve around 15 large freight railroads and over 600 small, regional roads. It plays an important role in the US national economy.

The effectiveness and the safety of railway operations depend on many factors including rail traffic rules, equipment reliability, general and safety management, and human factors. In particular with regard to human factors, it may be added that they are very important in the railway system just like in the case of any other complex system. Over the years, a large number of railway accidents resulting in many fatalities and a high economic cost have occurred due to human factors-related problems in the design and operation of railway systems around the world [1–3].

Over the years many publications concerning human factors in the railway system have appeared. Many of the publications on human error in that system are listed in the Appendix section of this book. This chapter presents various different aspects of human error in railways.

## 6.2  Facts, Figures, and Examples

Some of the facts, figures, and examples directly or indirectly concerned with human error in the railway system are as follows:

- During the period from 2000–2004, a total of 4,623 deaths and 51,597 injuries occurred in train accidents in the United States [4].
- During the period from 1900–1997, approximately 70% of the 141 accidents on four British main railway lines occurred due to human error [5, 6].

- In Norway, approximately 62% of the 13 railway accidents that caused fatalities or injuries during the period from 1970–1998 were the result of human error [6].
- In India, over 400 railway accidents occur annually and approximately 66% of these accidents are directly or indirectly, due to human error [7].
- In 2004, 53% of the railway switching yard accidents (excluding highway-rail crossing train accidents) in the United States were due to human factors causes [1].
- In 1988, in the United Kingdom (U.K.) 30 persons died and 69 were injured seriously at the Clapham Junction railway accident due to a human error in wiring [8].
- In 1999, human error and outdated equipment caused a fatal train wreck in south western Ontario, Canada [9].
- In 2005, due to a human error a subway train crash at Thailand Cultural Center Station, Bangkok, Thailand injured around 200 people [10].
- In 2005, due to a human error a three-train collision killed 133 people in Pakistan [11].
- In 1999, in the U.K. 31 people died and 227 persons were hospitalized in a train accident due to a human error [12].
- In 1989, in the U.K. a train accident at Purley on the London to Brighton line killed 5 persons and injured 88 persons. A subsequent investigation revealed that the accident was the result of a human error [3].

## 6.3  Railway Personnel Error-prone Tasks and Typical Human Error Occurrence Areas in Railway Operation

Railway personnel perform various types of tasks during their work environment. Some of these tasks are more prone to human error than the others. Nonetheless, some of the tasks performed by the railway personnel prone to serious human error are shown in Figure 6.1 [12].

Although there are many areas for the occurrence of human error in railway operation, the three typical ones are as follows [6]:

- Signal passing
- Train speed
- Signalling or dispatching

Each of the above three areas is discussed below, separately.

### 6.3.1 Signal Passing

This is a very important area because trains passing a signal displaying a stop, is a very dangerous occurrence, because it can lead to an immediate conflict with another train or trains. This situation is often referred to as Signal Passed at Danger (SPAD), and in the past, its occurrence has been quite frequent. The main reason for
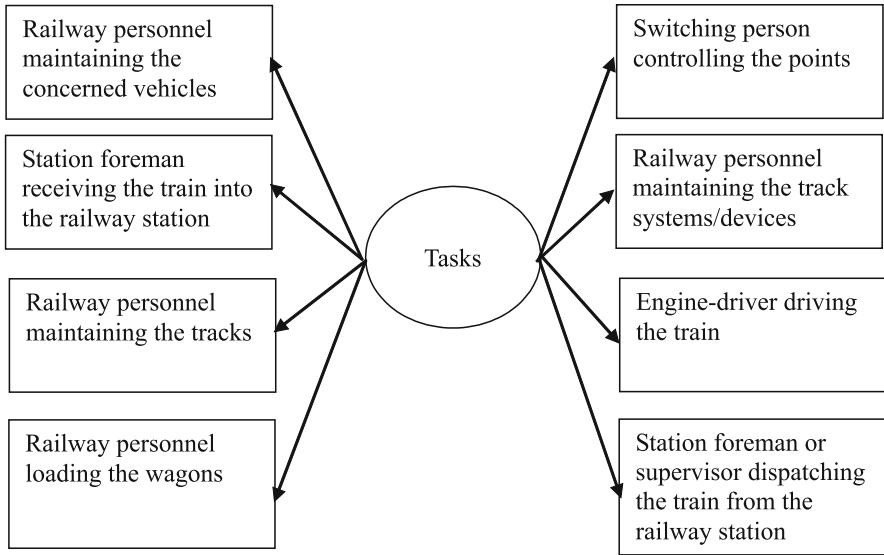
**Figure 6.1.** Some of the tasks performed by railway personnel prone to serious human error

this is the high frequency of approaching signalling points by train drivers during their work hours. Although, fortunately only a small percentage of SPAD) occurrences result in real accidents, but when they do happen they are often quite catastrophic.

Some of the important causes for the occurrence of a SPAD), are listed in Table 6.1 [12]. Each year, many SPAD) incidents occur in railway systems around the world. For example, the figure for the British Railway System, for the period 1996–1997, is 653 [6].

**Table 6.1.** Some of the causes for the occurrence of a Signal Passed at Danger (SPAD) event

| No. | Cause |
| --- | --- |
| 1 | Failure to see signal because of poor visibility |
| 2 | Misjudging the brakes' effectiveness under specific circumstances such as bad weather |
| 3 | Oversight or disregard to a signal |
| 4 | Over speeding with respect to braking performance and warning signal distance |
| 5 | Driver falls sleep or is unconscious |
| 6 | Misunderstanding of signalling aspect |
| 7 | Misjudging of which signal applies to the train in question |

A study of the SPAD) incidents conducted in the Netherlands for the period 1983-1984 reported a number of findings. Some of the main ones are as follows [6, 13]:

- A total of 214 SPAD) incidents occurred during the specified period.

- Around 90% of the SPAD) incidents occurred at stations or marshalling yards, and half them were concerned with arrival trains.
- There was no significant correlation between the train driver's experience or route knowledge and the frequency of SPAD) incidents.
- There were no significant differences in SPAD) occurrences between the various days of the week or the months of the year.
- There appear to be more SPAD) occurrences during the early hours of a work shift than the late hours of the shift.

### 6.3.2  Train Speed

This is another area that has resulted in numerous accidents because of the failure of the driver to reduce train speed as per specified for the route in question. The likelihood of over speeding and its associated consequences depend upon factors such as the type of speed restrictions and the circumstances around it. There are basically three types of speed restrictions that require driver response from his or her perspective: permanent speed restrictions, temporary or emergency speed restrictions, and conditional speed restrictions.

The permanent speed restrictions are imposed because of track curves or some existing infrastructure conditions on a particular section of a track in question. The temporary or emergency speed restrictions are imposed because of track maintenance work or temporary track deficiencies such as stability problems and frost heave. Finally, the conditional speed restrictions are imposed because of train route setting at a junction or station and the signalling aspect displayed in that regard.

### 6.3.3  Signalling or Dispatching

In the past many railway accidents have occurred in this area because of errors made by signalmen or dispatchers. Fortunately, with the application of modern technical devices the occurrence of human errors in this area has been reduced significantly [6].

## 6.4  Important Error Contributing Factors in Railways

Over a period of six months, a study of seven U.S. and Canadian Class I freight railroads and several regional railroads, concerning all Federal Railroad Administration (FRA) reportable train accidents, reported a total of 67 accidents/incidents [1]. Six of these accidents/incidents were further investigated in regard to error contributing factors. The investigation identified a total of 36 most probable contributing factors to the occurrence of these 6 accidents/incidents. These error contributing factors were classified under four categories as shown in Figure 6.2 [1]. These are operator acts, preconditions for operator acts, supervisory factors, and organizational factors. Under
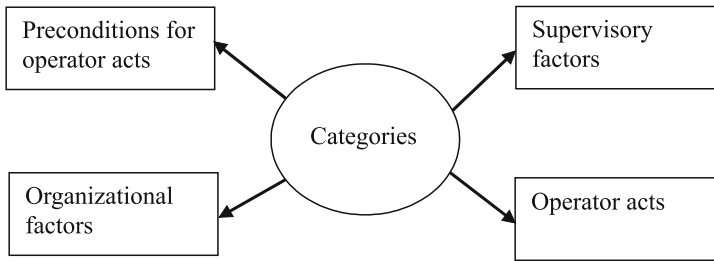
**Figure 6.2.** Four categories of error contributing factors in railways

each of these 4 categories a total of 12, 9, 6, and 9 contributing factors, respectively, were identified in the 6 accidents/incidents investigated. The contributing factors under the operator acts category were further divided into three groups: skilled-based errors, decision errors, and a routine contravention.

Similarly, the contributory factors belonging to the preconditions for operator acts category were divided into two groups: the technological environments and the physical environment. In the four of the six accidents/incidents investigated, eight contributing factors were associated with the technological environment. An example of these factors is an inability of the operator to determine which direction is forward for the locomotive. In regard to the physical environment, only one contributing factor, *i.e.*, inadequate lighting in the yard, was associated with one of the accidents/incidents.

The contributory factors belonging to the supervisory category were also divided into two groups: poor supervision and planned inappropriate operations. In three of the six accidents/incidents investigated, poor supervision was identified five times. The contributing factor, planned inappropriate operations, was associated with only one accident/incident.

Finally, the contributory factors belonging to the organizational factors category were also divided into two groups: the organizational process and resource management. In four of the six accidents/incidents, the organizational process contributing factors were identified six times. They were basically associated with poor practices and procedures governing remote control locomotive (RCL) operations and the application of the RCL Technology-Resource management was involved in two of the six accidents/incidents and associated with three contributing factors. Inadequate staffing was one of these three factors.

## 6.5  Human Error Analysis Methods

There are many methods used in reliability, quality, and safety fields to perform various types of analysis. Some of these methods can also be used to perform human error analysis in the railway system. These methods includes cause and effect diagram, fault tree analysis, failure modes and effect analysis, Pareto diagram, the Markov method, and the probability tree method. Some of these methods are de-

scribed in Chapter 5 and the others in References [14–16]. Nonetheless, two of these methods are described below.

## 6.5.1  Cause and Effect Diagram

This method or diagram was developed by K. Ishikawa in the early 1950s [17]. Sometimes the diagram is also referred to as "Fishbone diagram" because of its resemblance to the skeleton of a fish. Nonetheless, this diagram is used to identify the main causes of a given problem and to generate relevant ideas. Pictorially, the right side of the diagram, *i.e.*, the fish head, denotes the effect and the left side denotes all the possible causes. In turn, the causes are connected to the central line called the "Fish-spine." Usually, the steps listed below are followed to develop a cause and effect diagram [16, 17].

- Establish problem statement.
- Brainstorm to identify all possible causes for the problem under consideration.
- Develop appropriate main cause classifications by stratifying into natural groupings and process steps.
- Develop the diagram by following all the essential process steps.
- Fill in the problem or the effect in the box on the extreme right of the diagram.
- Refine cause classifications as considered appropriate by asking questions such as "Why does this condition exist? And "What causes this?.

Additional information on this method is available in References [14–17].

**Example 6.1**
After a careful investigation, it was established that there are four main causes, *i.e.*, cause I, II, III, and IV for a railway signalman to commit an error. In turn, there are two subcauses (*i.e.*, a and *b*) associated with Cause I, three (*i.e.*, *c*, *d*, and *e*) with Cause II, two (*i.e.*, *f* and *g*) with Cause III, and three (*i.e.*, *h*, *i*, and *j*) with Cause IV. Develop a cause and effect diagram. A cause and effect diagram for Example 6.1 is shown in Figure 6.3.
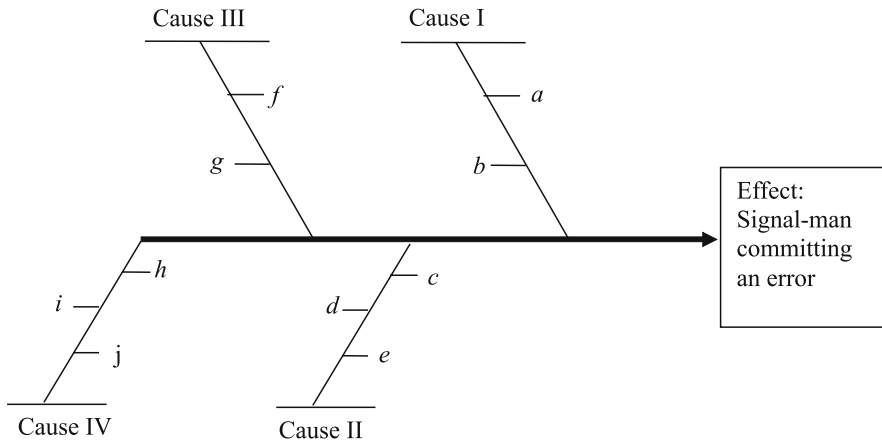
**Figure 6.3.** A cause and effect diagram for Example 6.1

## 6.5.2  Fault Tree Analysis

This method is widely used in industry to perform various types of reliability and safety studies and it was developed in the early 1960s at the Bell Laboratories [18]. Fault tree analysis starts by identifying an undesirable event, known as top event, associated with a system under consideration. Fault events that could cause the occurrence of the top event are generated and connected by logic operators AND and OR. The AND gate provides a True output (*i.e.*, fault) only when all its inputs are True (fault). In contrast, the OR gate provides a True output (*i.e.*, fault) when one or more of its inputs are True (fault).

This method is described in detail in Chapter 5. Its application to perform human error analysis in the railway system is demonstrated by the following example.

**Example 6.2**
After studying the functions performed by a train driver it was concluded that he/she can commit an error basically due to any of four causes: poor system design, poor training, poor outside environment, and carelessness. In turn, poor system design could be either due to poor control equipment design or poor work place design, and the poor outside environment could be either due to snow storm, rain storm, or dust storm.
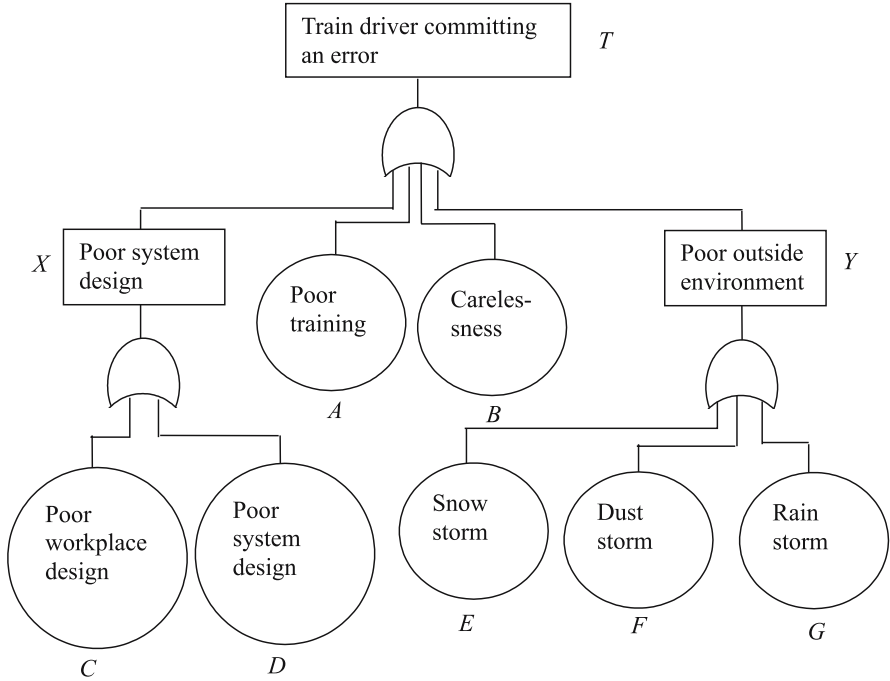
**Figure 6.4. A** fault tree for Example 6.2

Develop a fault tree for the top event, train driver committing an error, by using the fault tree symbols given in Chapter 5. Thus, with the aid of Chapter 5 fault tree symbols, a fault tree for the example is shown in Figure 6.4.

**Example 6.3**
In Figure 6.4 fault tree, calculate the probability of the train driver committing an error if the occurrence probability of independent events shown in circles is 0.04. Single capital letters in the fault tree diagram denote corresponding events (*e.g.*, *A*: poor training and *Y*: poor outside environment).

Thus, from Reference [19] and Chapter 5 the probability of occurrence of event *X* is

$$P(X) = 1 - \left[1 - P(C)\right]\left[1 - P(D)\right], \tag{6.1}$$

where
*P*(*C*)   is the probability of occurrence of event *C*.
*P*(*D*)   is the probability of occurrence of event *D*.

For the given values of P(C) and P(D), Equation (6.1) yields

$$P(X) = 1 - [1 - 0.04][1 - 0.04],$$
$$= 0.0784.$$

Similarly, the probability of occurrence of event $Y$ is

$$P(Y) = 1 - [1 - P(E)][1 - P(F)][1 - P(G)], \tag{6.2}$$

where
$P(E)$     is the probability of occurrence of event $E$.
$P(F)$     is the probability of occurrence of event $F$.
$P(G)$     is the probability of occurrence of event $G$.

For the given values of $P(E)$, $P(F)$, and $P(G)$, from Equation (6.2), we get

$$P(X) = 1 - [1 - 0.04][1 - 0.04][1 - 0.04],$$
$$= 0.1153.$$

Thus, the probability of occurrence of event $T$ (*i.e.*, the train driver committing an error) is

$$P(T) = 1 - [1 - P(X)][1 - P(A)][1 - P(B)][1 - P(Y)], \tag{6.3}$$

where
$P(A)$     is the probability of occurrence of event $A$.
$P(B)$     is the probability of occurrence of event $B$.

For the calculated values of $P(X)$ and $P(Y)$ and the given values of $P(A)$, and $P(B)$, Equation (6.3) yields

$$P(T) = 1 - [1 - 0.0784][1 - 0.04][1 - 0.04][1 - 0.1153],$$
$$= 0.2486.$$

Thus, the probability of the train driver committing an error is 0.2486. The fault tree of Figure 6.4 with the given and the above calculated event occurrence probability values is shown in Figure 6.5.
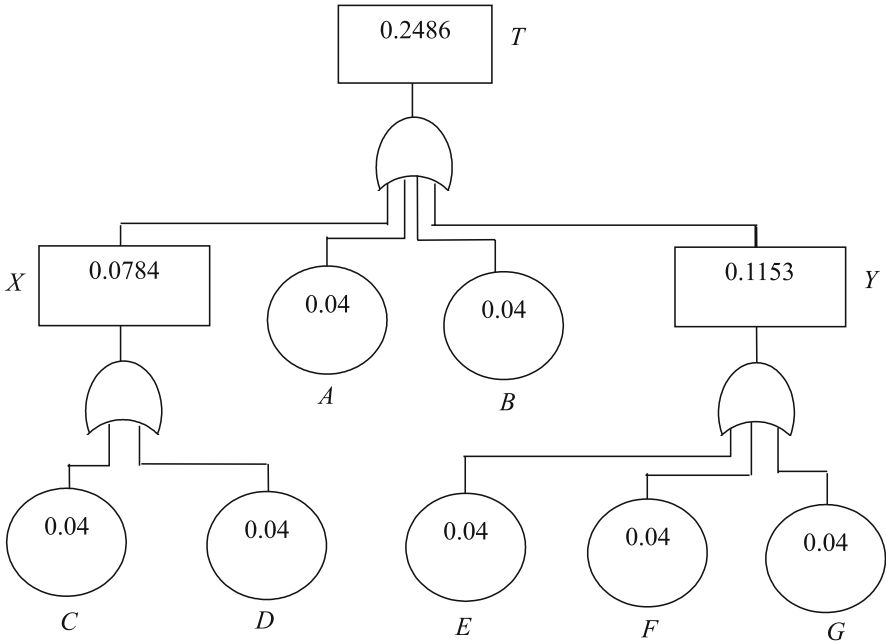
**Figure 6.5.** Redrawn Figure 6.4 fault tree with the calculated and given event occurrence probability values

# 6.6 Analysis of Railway Accidents Due to Human Error

Over the years, there have been many train accidents due to human error all over the world. This section presents a brief analysis of the following four train accidents that occurred directly or indirectly due to human error in the United Kingdom during the period 1988–1999 [3, 20]:

- The Ladbroke Grove accident
- The Purley accident
- The Southall accident
- The Clapham Junction accident

Each of the above four accidents is discussed below, separately.

## 6.6.1 The Ladbroke Grove Accident

The Ladbroke Grove accident occurred on October 5, 1999 at Ladbroke Grove, United Kingdom, where 2 trains collided and 31 people died. A subsequent inves-

tigation into the accident revealed that the direct cause of the accident was the failure of one of the train drivers to respond to a red signal. A further investigation into the direct cause revealed that the accident was due to a combination of factors such as listed below [3].

- Minimal amount of time available for observing the red signal aspect
- A novice driver who had driven just nine times on the route in question
- Short comings of the automatic warning system (AWS) driver aid
- Rather poor signal layout with obscuration by bridge girders
- Sun light on the red signal light diminished its relative contrast and intensity

## 6.6.2  The Purley Accident

This accident occurred on March 4, 1989 at Purley, United Kingdom, in which two passenger trains collided. More specifically, a fast moving train at a speed of about 50 miles per hour ran into the back of the slow moving train. As the result of this accident, 5 persons were killed and 88 persons were hospitalized.

A subsequent investigation into the accident revealed that the driver of the fast moving train passed through a series of signals at cautionary or danger aspects. More specifically, although the direct cause of the accident was the driver error, but the AWS intended to protect him was inadequate for its intended purpose.

## 6.6.3  The Southall Accident

This accident occurred on September 19, 1997 at Southall, United Kingdom in which a high-speed passenger train collided with an empty freight train. The accident took place at a track where four main rail lines were joined by crossovers between the adjacent tracks. Six persons were killed and 150 injured in the accident.

A subsequent investigation into the accident revealed that the direct cause of the accident was the high-speed train driver's failure to respond to a series of cautionary and danger signals. The main cause for this was the blockage of the driver's view of the signals by work on overhead line electrification. In fact, the height of many of the signals was raised as much as 18 feet above the ground level.

## 6.6.4  The Clapham Junction Accident

This accident occurred in December 1988 at the Clapham Junction Station in London, United Kingdom, in which two commuter trains collided. A total of 35 people were killed in the accident. A subsequent investigation into the accident revealed that the main cause of the accident was a signal fault, resulting from a few days earlier working in the main signal box controlling trains at Clapham Junction. More specifically, the work was concerned with the installation of a modern system of electrical relays.

As the result of this accident, a total of 93 recommendations to improve methods of performing and supervising maintenance work, and to adopt appropriate quality control techniques for ensuring a proper execution of the maintenance activity, were made.

## 6.7  A Useful Checklist of Statements for Reducing the Occurrence of Human Error in Railways

This section presents a checklist of statements considered useful for ensuring good human factors-related practices in railway projects. In turn, this exercise will be useful to reduce the occurrence of human error in the railway system. These statements are as follows [21]:

- People performing human factors tasks are competent to do so.
- People performing human factors tasks are given sufficient resources and authority.
- Human factors receive the same degree of importance as any other area of safety engineering.
- A programme-wide human factors coordinator is appointed.
- The representation of human error is integrated effectively with other safety analysis aspects.
- The necessary and existing competency of end users is evaluated effectively.
- Human errors are identified, modeled, and controlled effectively.
- A broad range of information concerning human factors is being communicated in an effective manner.
- All dependencies between human actions are understood clearly.
- Human reliability analysis methods are being used correctly and effectively.
- Human factors requirements are integrated effectively into the system requirements.
- The tasks being performed are clearly understood, in order to identify human error sources.
- The human factors planning aspect is fully integrated into the general project planning.
- The process of human error identification is fully integrated into the general process of hazard identification, within the project framework.
- When considering risk reduction techniques all potential system users are involved.
- The identification, evaluation, and reduction of risk from human error is being considered as a main element of any safety process.
- All appropriate aspects of human factors are fully integrated into the safety argument.

- The project aims to design systems for helping all potential users avoid or recover from hazards.
- All aspects of human factors are being considered from the outset of a given project.

## 6.8  Problems

1. Write an essay on human error in railways.
2. List at least eight tasks performed by railway personnel that are prone to serious human errors.
3. Discuss the term Signal Passed at Danger (SPAD).
4. List at least five important causes for the occurrence of a signal passed at Danger (SPAD) event.
5. What are the important error contributing factors in railways?
6. List at least six methods that can be used to perform human error analysis in the railway system.
7. Compare the following two railway accidents that occurred in the United Kingdom:
   - The Ladbroke Grove accident
   - The Clapham Junction accident
8. List at least 12 statements for use during the execution of a railway project that can, directly or indirectly, help to reduce the occurrence of human error in the railway system.
9. List at least five important facts and figures, directly or indirectly, concerned with the occurrence of human error in the railway system.
10. Discuss the following items with respect to the occurrence of human error in railway operation:
    - Train speed
    - Signaling or dispatching

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# 7

# Human Error in Shipping

## 7.1 Introduction

Humans have relied on oceans, lakes , and rivers to ship goods from one end to another throughout the recorded history. Today, over 90% of the world's cargo is transported by merchant ships due to various reasons, including that it is the cheapest form of transportation. In fact, from the early 1920s through the end of the century, the total number of merchant ships in the world increased from under 30,000 to about 90,000 [1, 2]. Also, today a large number of ships are being used for various military purposes throughout the world.

A modern ship is comprised of many elements (systems), each of which has a varying degree of effect on the overall performance of that ship. Although many of these systems may be fully automated, they still require a degree of human intervention (*e.g.*, set initial tolerances or respond to alarms). Also, the nonautomated systems may require direct human inputs for their operation and maintenance, humans to interact with other humans, *etc.* Needless to say, as humans are not one hundred percent reliable, the past experiences indicate that in the shipping industry around 80% of all accidents are rooted in human error [3].

This chapter presents various important aspects of human error in shipping.

## 7.2 Facts, Figures, and Examples

Some of the facts, figures, and examples directly or indirectly related to human error in shipping are as follows:

- Human error costs the maritime industry $541 million per year, as per the findings of the United Kingdom Protection and Indemnity (UK P&I) Club [4].
- A study of 6091 major accident claims (*i.e.*, over $100,000) associated with all classes of commercial ships, conducted over a period of 15 years by the UK P & I Club, revealed that 62% of the claims were attributable to human error [4–6].
- Human error contributes to 84–88% of tanker accidents [7, 8].

- Human error contributes to 79% of towing vessel groundings [7, 9].
- Over 80% of marine accidents are caused or influenced by human and organization factors [10, 11].
- Around 60% of all US Naval Aviation-Class A accidents (*i.e.*, the ones that result in death, permanent disability, or loss of $1 million) were due to various human and organization factors [10, 12].
- Human error contributes to 89–96% of ship collisions [7, 13].
- A Dutch study of 100 marine casualties found that human error contributed to 96 of the 100 accidents [7, 14].
- In February 2004, a chemical/product tanker, the *Bow Mariner* sunk because of an on-board explosion due to a human error and 18 crew members died [15].
- The collision of the MV Santa Cruz II and the USCGC Cuyahoga due to a human error resulted in the death of 11 Coast Guardsmen [7, 16].
- The grounding of the ship *Torrey Canyon* due to various human errors resulted in the spilling of 100,000 tons of oil [7, 16].

## 7.3  Human Factors Issues Facing the Marine Industry

Today, there are many human factors issues facing the marine industry that directly or indirectly influence the occurrence of human error. Some of the important ones are shown in Figure 7.1 [7, 17–21]. These are poor communications, fatigue, poor automation design, poor general technical knowledge, poor maintenance, decisions based on inadequate information, faulty policies, practices, or standards, poor knowledge of own ship systems, and hazardous natural environment.

The issue of "poor communication" is concerned with communications between shipmates, between masters and pilots, ship to ship, *etc.* Around 70% of all major
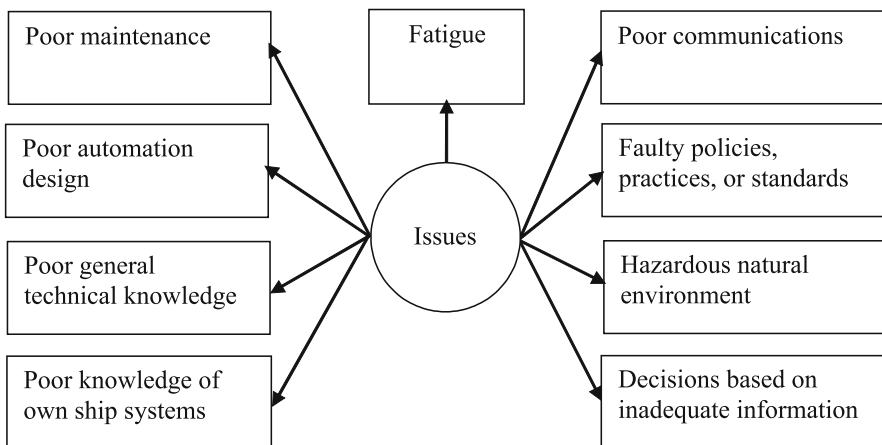


**Figure 7.1.** Important human factor issues facing the marine industry

marine allisions and collisions took place when a State or federal pilot was directing one or both vessels [20]. In this regard, better training and procedures can help to promote better communications and coordination on and between vessels. Fatigue has been pointed out as the "pressing issue" of mariners in two different studies [17, 18], and another study revealed that fatigue contributed to 33% of the vessel injuries and 16% of the casualties [21]. Poor automation design is a challenging issue because poor equipment design pervades almost all shipboard automation, and as per Reference [14] poor equipment design was a causal factor in one-third of major marine casualties [14]. In this regard, a proper consideration by equipment designers to factors such as how a given piece of equipment will support the mariner's tasks and how it will integrate into the entire equipment "suite" used by the mariner can be a very helpful step.

The issue of "poor general technical knowledge" is concerned with the poor understanding of mariners of how the automation works or under what conditions it was designed to work effectively. Consequently, mariners sometimes commit errors in using the equipment, and, in fact, according to one study, this problem alone was responsible for 35% of casualties [14].

Poor maintenance is another important issue because poor maintenance of ships can lead to situations such as dangerous work environments, lack of functional backup systems, and crew fatigue from the need to carry out emergency repairs. In fact, the past experiences indicate that poor maintenance is a leading cause of fires and explosions in ships [13]. The issue of "decisions based on inadequate information" is concerned with mariners making navigation-related decisions on inadequate information. They often tend to rely on either a favoured piece of equipment or their memory and in other cases, critical information could be lacking or incorrect altogether. Situations such as these can lead to navigation errors.

The issue of faulty policies, practices, or procedures covers a variety of problems including the lack of available precisely written and comprehensible operational procedures aboard ship, management policies that encourage risk-taking, and the lack of standard traffic rules from port to port.

Poor knowledge of the ships' systems is a frequent contributing factor to marine casualties because of various difficulties encountered by crews and pilots working on ships of different sizes, with different types of equipment and carrying different cargoes. Furthermore, 78% of the mariners surveyed cited the lack of ship-specific knowledge an important problem [17]. Nonetheless, actions such as better training, standardized equipment design, and an effective method of assigning crew to ships can be quite useful to overcome this problem.

The issue of hazardous natural environment is concerned with currents, winds, and fog that can make treacherous working conditions; thus a greater risk for casualties. This problem could be overcome by considering these three factors (*i.e.*, currents, winds, and fog) into ships and equipment design as well as adjusting ship associated operations on the basis of hazardous environmental conditions.

## 7.4  Risk Analysis Methods for Application in Marine Systems

There are many sources of risk to marine systems including human error, external events, equipment failure, and institutional error [22]. Risk analysis or assessment helps to answer basically three questions, as shown in Figure 7.2. Over the years, in areas such as reliability and safety, many methods and techniques have been developed to perform various types of analysis. Many of these methods can be used to perform risk analysis in marine systems. Nine of these methods are shown in Figure 7.3 [22–26]. Each of these methods with respect to risk assessment, is briefly discussed below [22]:

- **Fault tree analysis (FTA).** This is a qualitative/quantitative and an inductive modeling approach, and is quite useful to identify combinations of equipment failures and human errors that can lead to an accident. An application of FTA to oil tanker grounding is presented in a subsequent section and additional information on FTA is available in Reference [27].
- **Failure modes and effect analysis (FMEA).** This is a qualitative/quantitative and an inductive modeling approach that identifies equipment (components) failure modes and their impacts on the surrounding components and the system. Additional information on the method is available in Reference [28].
- **Checklists.** This is a qualitative approach, and it insures that organizations are complying with standard practices. Additional information on the method is available in Reference [29].
- **Safety/review audits.** This is a qualitative approach and is quite useful to identify equipment conditions or operating procedures that could result in a casualty or lead to property damage or environmental impacts. Additional information on the method is available in References [22, 25].
- **Hazard and operability study (HAZOP.** This is a qualitative approach that was developed in the chemical industry and is a form of FMEA. The method is quite useful to identify system deviations and their associated causes that can result in undesirable consequences and to determine recommended actions for reducing the frequency/deviation consequences. Additional information on the method is available in References [26, 30].
- **Probabilistic risk analysis (PRA).** This quantitative methodology was developed by the nuclear engineering community to assess risk. PRA may use a combination of risk assessment approaches and is described in detail in Reference [31].
- **"What-if" analysis.** This is a qualitative approach that identifies hazards, hazardous conditions, or specific accident events that could lead to undesirable consequences. Additional information on the method is available in References [22, 25, 32, 33].
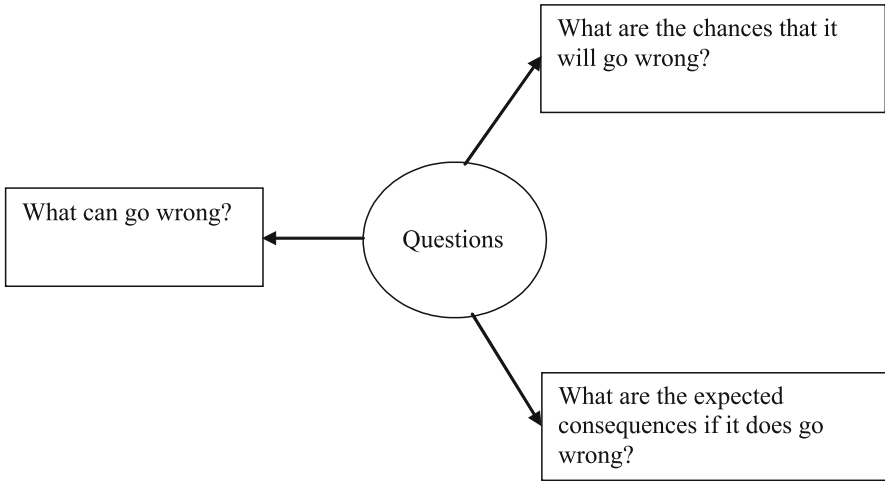
**Figure 7.2.** Questions answered by risk assessment or analysis
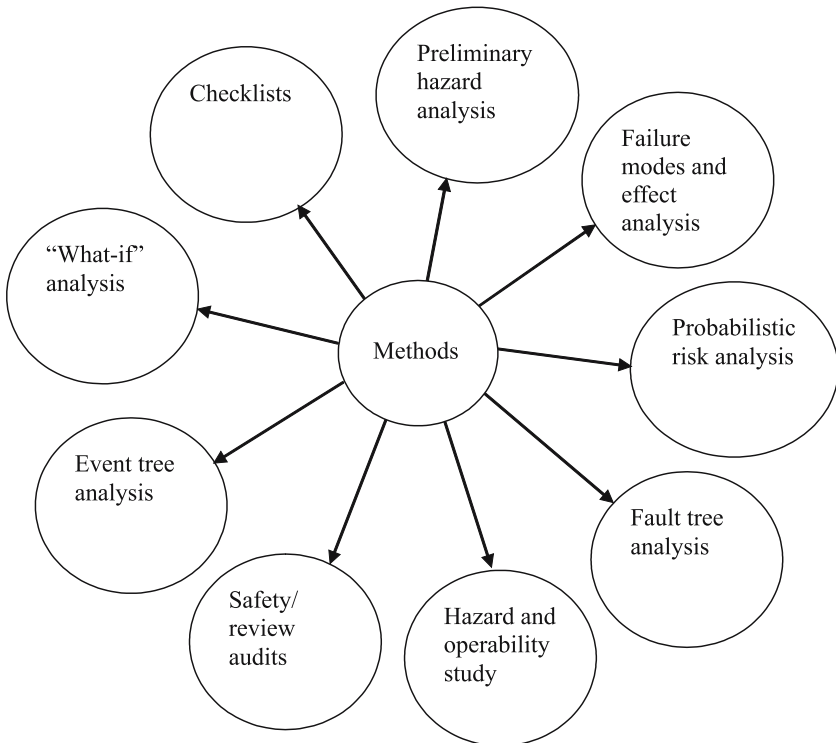


**Figure 7.3.** Methods for performing risk analysis in marine systems

- **Preliminary hazard analysis.** This is a qualitative and an inductive modeling approach, and is quite useful to identify and prioritize hazards leading to undesirable consequences early in the system life cycle. In addition, it evaluates recommended actions for reducing the frequency/consequences of the prioritized hazards. Additional information on the method is available in References [22, 25, 26].
- **Event tree analysis (ETA).** This is a quantitative and an inductive modeling approach that identifies various consequences of events, both successes and failures that can result in an accident. Additional information on ETA is available in References [22, 26, 34].

## 7.5  Fault Tree Analysis of Oil Tanker Groundings

Over the years, as oil tankers have become bigger, the tolerance for error has decreased with an increase in consequences. The United States Coast Guard (USCG)
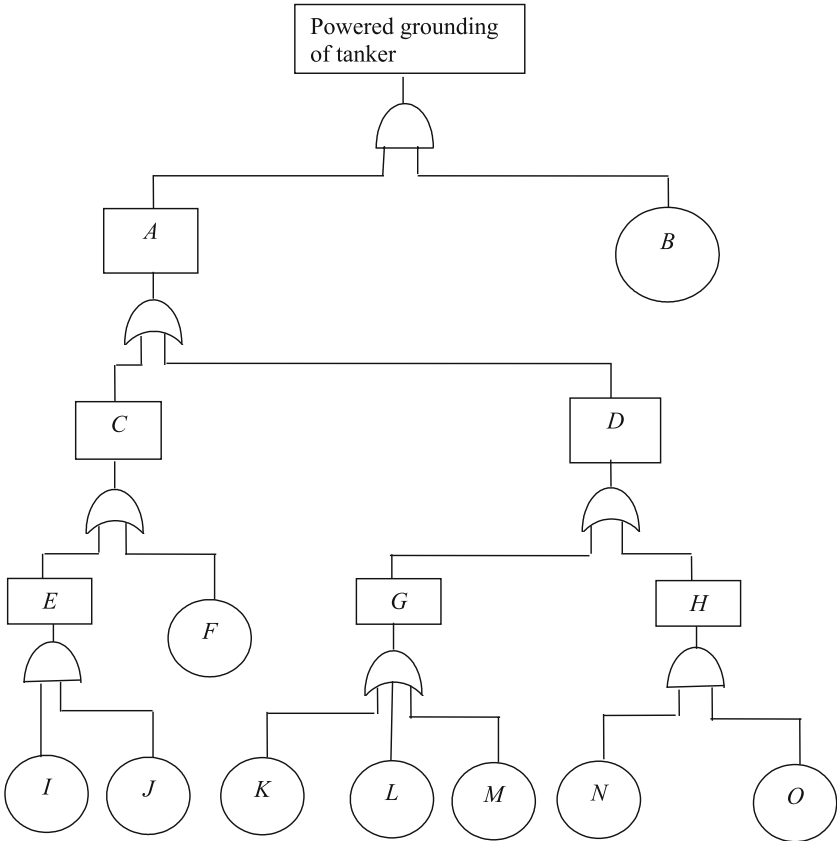


**Figure 7.4.** A fault tree for the top event: powered grounding of tanker

has identified the tanker industry as a high-risk industry with a high potential for improvement [35]. Thus, it means that a systematic approach must be undertaken to identify all tanker associated possible accidents and their consequences, so that they can be reduced to a minimum level through appropriate safety-related measures. Fault tree analysis is a useful tool to perform various types of tanker safety-related analysis, directly or indirectly, concerning human error.

Using the fault tree symbols defined in Chapter 5, a simple fault tree for the top event, powered grounding of tanker, is shown in Figure 7.4 [35]. This top event may be described as an event that occurs when a tanker collides with the shoreline while underway because of lack of crew vigilance and navigational error. The capital letters in rectangles and circles of Figure 7.4 diagram denote intermediate and basic fault events associated with the tanker, respectively. Each of these capital letters is defined below [35].

- *A*: The actual tanker course proceeds down a hazardous track.
- *B*: Able to follow a safe track.
- *C*: The tanker course deviates from a safe and desired path or track.
- *D*: The desired tanker track is unsafe or hazardous.
- *E*: Inadequate action to eliminate error and difference error is detected.
- *F*: No difference error detected.
- *G*: Errors committed in planning track.
- *H*: Planning information is incorrect and no errors in planning.
- *I*: Inadequate action to eradicate error.
- *J*: Difference error is detected.
- *K*: Incorrect information is used.
- *L*: Information is used incorrectly.
- *M*: Inadequate amount of information is used.
- *N*: No errors committed in planning.
- *O*: Planning information is incorrect.

**Example 7.1**

Assume that in Figure 7.4, the probabilities of occurrence of independent events, *B*, *F*, *I*, *J*, *K*, *L*, *M*, *N*, and *O* are 0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, 0.08, and 0.09, respectively. Calculate the probability of occurrence of the top event: Powered grounding of tanker, by using equations presented in Chapter 5.

Thus, from Chapter 5 the probability of occurrence of event *G* is

$$P(G) = 1 - \left[1 - P(K)\right]\left[1 - P(L)\right]\left[1 - P(M)\right] \tag{7.1}$$

where
$P(K)$ is the probability of occurrence of event *K*.
$P(L)$ is the probability of occurrence of event *L*.
$P(M)$ is the probability of occurrence of event *M*.

For the specified values of $P(K)$, $P(L)$, and $P(M)$, Equation (7.1) yields

$$P(G) = 1 - [1 - 0.05][1 - 0.06][1 - 0.07],$$
$$= 0.1695.$$

Similarly, from Chapter 5 the probability of occurrence of event $H$ is

$$P(H) = P(N)P(O),\qquad(7.2)$$

where
$P(N)$ is the probability of occurrence of event $N$.
$P(O)$ is the probability of occurrence of event $O$.

For the given values of $P(N)$ and $P(O)$, from Equation (7.2), we get

$$P(H) = (0.08)\,(0.09),$$
$$= 0.0072.$$

Similarly, the probability of occurrence of event $E$ is

$$P(E) = P(I)\,P(J),\qquad(7.3)$$

where
$P(I)$  is the probability of occurrence of event $I$.
$P(J)$  is the probability of occurrence of event $J$.

For the specified values of $P(I)$ and $P(J)$, Equation (7.3) yields

$$P(E) = (0.03)(0.04),$$
$$= 0.0012.$$

In a similar manner to Equation (7.1), the probability of occurrence of event $C$ is

$$P(C) = 1 - [1 - P(E)][1 - P(F)],\qquad(7.4)$$

where
$P(F)$  is the probability of occurrence of event $F$.

For the above calculated and given values of $P(E)$ and $P(F)$, respectively, from Equation (7.4), we get

$$P(C) = 1 - [1 - 0.0012][1 - 0.02],$$
$$= 0.0212.$$

Similarly, the probability of occurrence of event $D$ is given by

$$P(D) = 1 - [1 - P(G)][1 - P(H)].\qquad(7.5)$$

For the calculated values of $P(G)$ and $P(H)$, Equation (7.5) yields

$$P(D) = 1 - [1 - 0.1695][1 - 0.0072],$$
$$= 0.1755.$$

Similarly, the probability of occurrence of event A is

$$P(A)=1-\left[1-P(C)\right]\left[1-P(D)\right]. \tag{7.6}$$

For the calculated values of $P(C)$ and $P(D)$, from Equation (7.6), we get

$$P(A)=1-[1-0.0212][1-0.1755],$$
$$=0.1930.$$

Thus, for the above calculated and given values of $P(A)$ and $P(B)$, respectively, the probability of occurrence of the top event: Powered grounding of tanker, is given by

$$=P(A)P(B),$$
$$=(0.1930)(0.01),$$
$$=0.0019.$$

## 7.6  Safety Management Assessment System to Identify and Evaluate Human and Organizational Factors in Marine Systems

Past experiences indicate that a very high percentage of major marine accidents are either caused or influenced by humans and organizations (errors). The safety management assessment system (SMAS) is a useful tool to reduce such accidents [36]. In fact, it was developed specifically to assess marine systems such as ships and marine terminals with respect to human and organization factors. SMAS may simply be described as a screening approach that chooses and trains operators of the system under consideration for conducting a self-assessment. SMAS is composed of three main components as shown in Figure 7.5 [36].

The assessment process consists of three phases: in-office evaluation of information (*i.e.*, at the on-shore office), system visits (*i.e.*, at the actual facility), and final review and assessment (*i.e.*, at the on-shore office). The time required for the process is about five days.

Assessors make comparisons and evaluate human and organization factors by choosing appropriate ranges and providing appropriate comments to capture the element of certainty. Instruments (*i.e.*, computer programs) assist the assessment process by performing appropriate calculations, placing them in a database, and using pre-programmed reports to display the assessment results.

A filed test of SMAS at a marine terminal in California concluded the following [36]:

• A facilitator is required in using SMAS.
• It is possible to accomplish, an assessment of a system for human and organization factors, within five days.
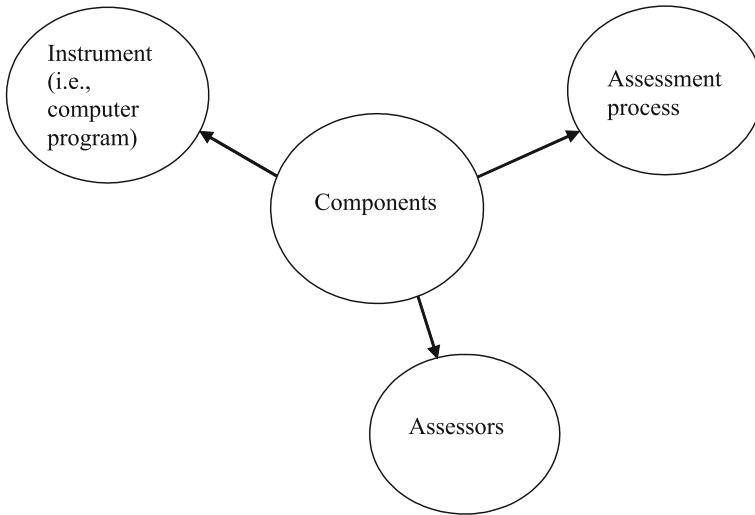
**Figure 7.5.** Safety management assessment system (SMAS) main components

- The existence of the computer program is crucial in performing the assessment.
- A careful selection and proper training of operators as assessors is critical to produce consistant results.
- The use of operators as assessors is important because they are the best people to provide insight into their system.

Additional information on SMAS is available in Reference [36].

## 7.7  Reducing the Manning Impact on Shipping System Reliability

In a reduced manning environment, the overall shipping system reliability is impacted both negatively and positively. For example, with the human as an element of the system, the lesser number of humans could very well equate to reduced operating capacity. In contrast, the system operates better when machines or automatic software comprise the critical operating parameters of the system [37]. Nonetheless, the expected impacts of a reduced manning design on shipping system reliability can be described with respect to human systems integration approaches, for improving human reliability. Three of these approaches are as follows [37]:

- Reduce the occurrence of human error incidence
- Eliminate or minimize human error impacts
- Improve mean time between failures (MTBF) under the reduced manning environment

In the case of the first approach, *i.e.*, reduce the occurrence of human error incidence, human error rates are reduced through means such as application of human engineering design principles, job task simplification, and error likelihood modeling or analysis.

In the case of the second approach, *i.e.*, eliminate or minimize human error impacts, human error impacts are eliminated or minimized through actions such as designing the system to be error tolerant, and designing the system that enables the human/system to recognize that an error has occurred as well as to correct the error prior to any damage.

In the case of the third approach, *i.e.*, improve MTBF) under the reduced manning environment, one typical method for improving MTBF) is to design or choose highly reliable system parts as well as design the interfaces to optimize the use of these parts.

## 7.8  Problems

1.  Write an essay on human error in shipping.
2.  List at least seven facts and figures concerned with human error in shipping.
3.  Discuss five most important human factors issues facing the marine industry.
4.  What are the typical questions answered by risk assessment?
5.  Discuss the following two methods that can be used to perform risk analysis in marine systems:
    - Failure modes and effect analysis
    - Event tree analysis
6.  Assume that in Figure 7.4, the probability of occurrence of independent events *B*, *F*, *I*, *J*, *K*, *L*, *M*, *N*, and *O* is 0.05. Calculate the probability of occurrence of the top event: Powered grounding of tanker.
7.  Describe safety management assessment system.
8.  Discuss the term "reducing the manning impact on shipping system reliability."
9.  Compare hazard and operability study with failure modes and effect analysis in regard to marine systems.
10. List four methods that can be used to perform quantitative risk analysis in marine systems.

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# 8

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# Human Error in Road Transportation Systems

## 8.1  Introduction

Each year billions of dollars are spent to construct or build roads and motor vehicles throughout the world to move people and goods from one point to another. Commercial motor vehicle operations account for a large sum of annual revenues throughout the world. For example, in the United States alone these revenues are around $400 billion per year, representing over 80% of the nation's freight bill [1].

In road transportation systems, safety is a pressing problem because throughout the world around 0.8 million road accident fatalities and 20–30 million injuries occur annually [2–3]. Although, around 70% of these fatalities and injuries occur in the developing or emerging world, the human error is believed to be an important factor in the occurrence of such events irrespective of developed or developing world. There could be many factors for the occurrence of human error including poor vehicle design, poor road design, and negligence. Nowadays, because of factors such as these, increasing attention is being given to human factors in road transportation systems, in order to, directly or indirectly, reduce the occurrence of human error.

This chapter presents various different aspects of human error in road transportation systems.

## 8.2  Facts and Figures

Some of the facts and figures, directly or indirectly, concerning human error in road transportation systems are as follows:

- Each year over 40,000 people die and another 3.5 million people are injured in the United States [4]. Furthermore, the annual cost of highway crashes to the country is over $150 billion [4].
- During the period 1966–1998, over 70% of bus accidents were due to driver error in five developing countries: Thailand, Nepal, India, Zimbabwe, and Tanzania [2].

- As per Reference [5], human error is cited more frequently than mechanical problems in approximately 5,000 truck-related deaths that occur each year in the United States.
- A study of car-truck crashes revealed that most of these crashes were due to human error either committed by the truck driver or car driver [1].
- About 65% of motor vehicle accidents are attributable to human error [6].
- As per a South African Press Association (SAPA) report, around 57% of all bus accidents in South Africa are caused by human error [7].
- As per the findings of a study concerning heavy truck accidents, about 80% of the accidents are caused by human error [8].
- The annual cost of road crashes worldwide is estimated to be around $500 billion [9].
- As per References [9–11], road traffic injuries will become the 3rd largest cause of disabilities in the world by the year 2020.

## 8.3  Operational Influences on Commercial Driver Performance

Past experiences indicate that operational influences are an important factor on the performance of commercial drivers with respect to the occurrence of human error. Although all drivers perform their tasks in a vehicle functioning within the physical environment of a road, but a principal difference lies in the operational environment of commercial motor vehicle transportation. More specifically, commercial drivers work against the backdrop of a complex operational environment that includes items such as listed below [1].

- **Practices outlined by the company management.** They include scheduling, selection, training, and incentives for safe work performance.
- **Work requirements.** An example of these requirements is customer delivery schedules.
- **Government or other body regulations and penalties for violations.**
- **Labour policies and traditions.**

Finally, it may be added that to the greatest extent possible, the operational environment must optimize safety with respect to human error while sustaining productivity to an acceptable level.

## 8.4  Types of Driver Errors, Ranking of Driver Errors, and Common Driver Errors

There are various types of driver errors that can result in an accident. References [12, 13] have classified such errors under four distinct categories as shown in
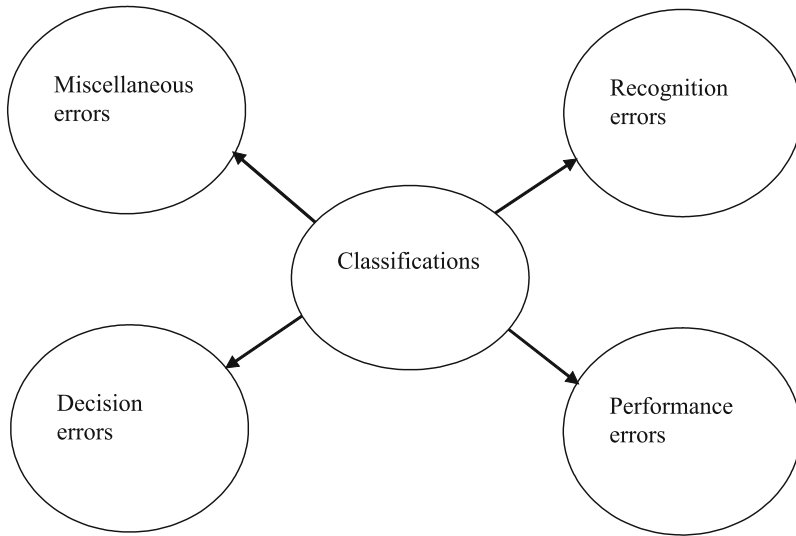
**Figure 8.1.** Classification of driver errors that can result in accidents

Figure 8.1. In a decreasing frequency of occurrence, they are recognition errors, decision errors, performance errors, and miscellaneous errors.

Over the years many studies have attempted to rank the occurrence of driver errors.

The results of two of these studies (I and II) are presented below. In study I, the occurrence of various driver errors was ranked from highest frequency of occurrence to the lowest frequency of occurrence as presented in Table 8.1 [12, 13]. Similarly, in study II, various driver errors/causes were ranked from highest frequency of occurrence to the lowest frequency of occurrence as follows [14]:

- Lack of care
- Too fast
- Looked, but failed to see
- Distraction

**Table 8.1.** Ranking of driver errors that contribute to accidents

| Rank (highest occurrence to lowest occurrence) | Error description |
|---|---|
| 1 | Improper lookout |
| 2 | Excessive speed |
| 3 | Inattention |
| 4 | False assumption |
| 5 | Improper manoeuvre |
| 6 | Internal distraction |

- Inexperience
- Failure to look
- Incorrect path
- Poor attention
- Improper overtaking
- Wrong interpretation
- Lack of judgment
- Misjudged distance and speed
- Following too closely
- Difficult manoeuvre
- Reckless or irresponsible
- Incorrect decision/action
- Lack of education or road craft
- Faulty signalling
- Poor skill

Drivers make many different types of errors. The most common driver errors are shown in Figure 8.2 [14, 15].
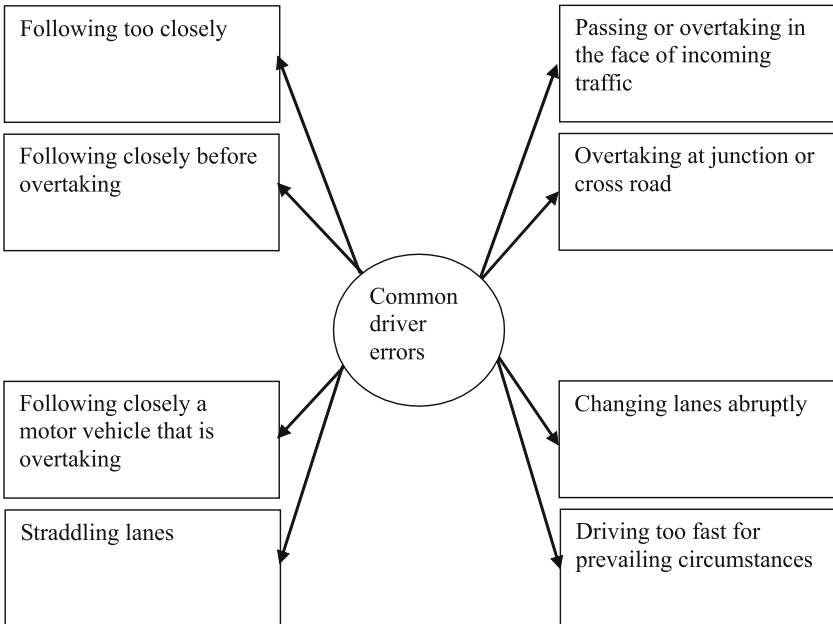


**Figure 8.2.** Most common driver errors

## 8.5 Methods for Performing Human Error Analysis in Road Transportation Systems

There are many methods developed in reliability, safety, and other fields for conducting various types of analysis [16, 17]. Some of these methods can also be used to conduct human error analysis in road transportation systems. These methods include fault tree analysis, Markov method, failure modes and effect analysis, and cause and effect diagram [16, 17]. The applications of fault tree analysis and Markov method to perform human error analysis in road transportation systems are demonstrated below, separately.

### 8.5.1 Fault Tree Analysis

This method was developed in the early 1960s and is widely used to perform various types of reliability and safety studies in the industrial sector. The method is described in detail in Chapter 5 and its application to conduct human error analysis in road transportation systems is demonstrated through the following example.

**Example 8.1**
After a careful study of functions performed by a motor vehicle driver, it was concluded that he/she can make an error due to one of the following eight causes:

- Heavy traffic
- Poor highway design
- Fatigue
- Poor weather
- Poor training
- Carelessness
- Conversation with others
- Poor workplace design

In turn, poor weather could be either due to snow storm, rain storm, dust storm, or freezing rain. Similarly, conversation with others could be either on cell phone or with someone in the vehicle. Finally, poor workplace design could be because of poor control panel design or poor seating.

Develop a fault tree for the top event, motor vehicle driver making an error, by using the fault tree symbols given in Chapter 5. Using the Chapter 5 fault tree symbols, a fault tree for the example was developed and is shown in Figure 8.3.

**Example 8.2**
In Figure 8.3 fault tree, calculate the probability of the motor vehicle driver making an error if the occurrence probability of independent events shown in circles is 0.02.
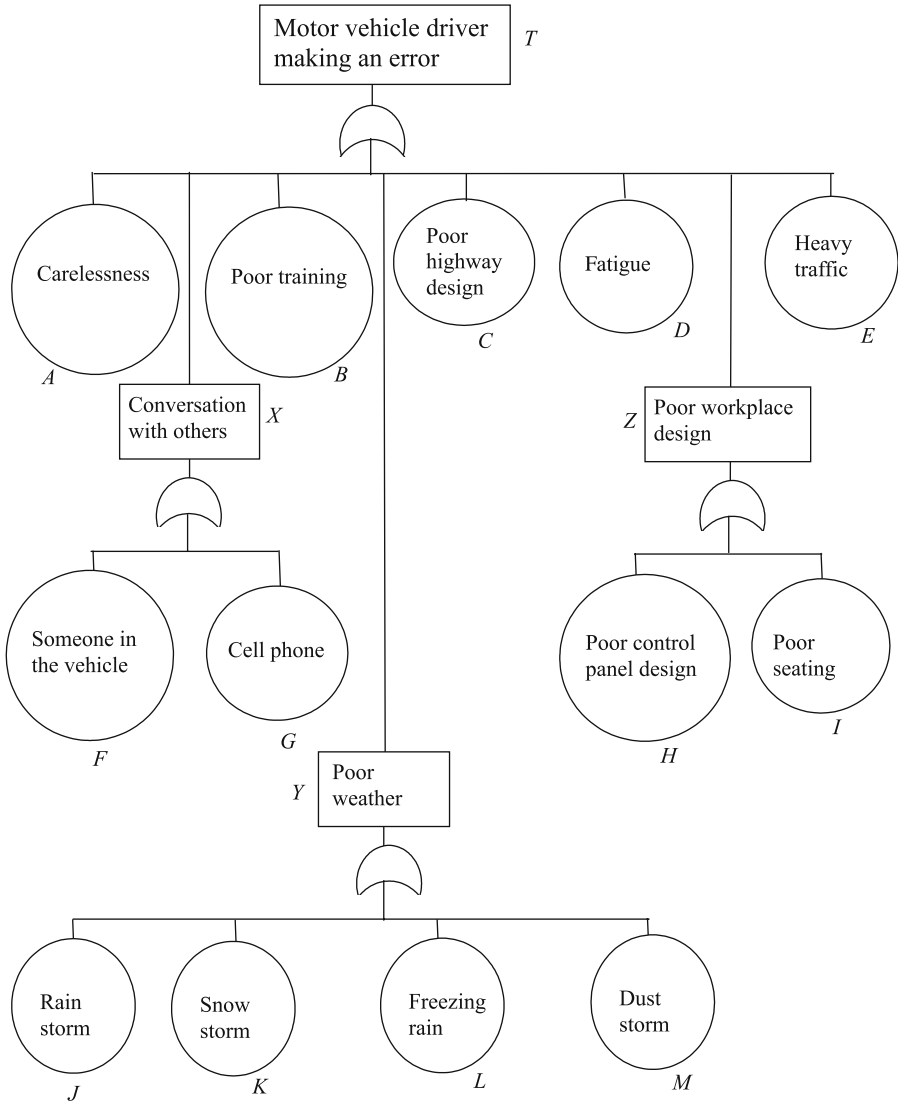
**Figure 8.3.** A fault tree for Example 8.1

Single capital letters in the fault tree diagram denote corresponding events (*e.g.*, *T*: Motor vehicle driver making an error).

From Chapters 2, 5, and Reference [16], the probability of occurrence of event *X* is given by

$$P(X)=1-\left[1-P(F)\right]\left[1-P(G)\right],\qquad(8.1)$$

where
$P(F)$ is the probability of occurrence of event *F*.

$P(G)$ is the probability of occurrence of event $G$.

For the specified values of $P(F)$ and $P(G)$, Equation (8.1) yields

$$P(X)=1-[1-0.02][1-0.02],$$
$$=0.0396.$$

Similarly, from Chapters 2, 5, and Reference [16], the probability of occurrence of event $Y$ is

$$P(Y)=1-\left[1-P(J)\right]\left[1-P(K)\right]\left[1-P(L)\right]\left[1-P(M)\right], \qquad (8.2)$$

where
$P(J)$  is the probability of occurrence of event $J$.
$P(K)$ is the probability of occurrence of event $K$.
$P(L)$  is the probability of occurrence of event $L$.
$P(M)$ is the probability of occurrence of event $M$.

For the given values of $P(J)$, $P(K)$, $P(L)$, and $P(M)$, Equation (8.2) yields

$$P(Y)=1-[1-0.02]^{4},$$
$$=0.0776.$$

In similar manner, the probability of occurrence of event $Z$ is

$$P(Z)=1-\left[1-P(H)\right]\left[1-P(I)\right], \qquad (8.3)$$

where
$P(H)$ is the probability of occurrence of event $H$.
$P(I)$  is the probability of occurrence of event $I$.

For the specified values of $P(H)$ and $P(I)$, from Equation (8.3), we get

$$P(Z)=1-[1-0.02]^{2},$$
$$=0.0396.$$

Thus, the probability of occurrence of event $T$ (*i.e.*, the motor vehicle driver making an error) is given by

$$P(T)=1-\left[1-P(A)\right]\left[1-P(X)\right]\left[1-P(B)\right]\left[1-P(Y)\right]\left[1-P(C)\right]$$
$$\left[1-P(D)\right]\left[1-P(Z)\right]\left[1-P(E)\right], \qquad (8.4)$$

where
$P(A)$  is the probability of occurrence of event $A$.
$P(B)$  is the probability of occurrence of event $B$.
$P(C)$  is the probability of occurrence of event $C$.
$P(D)$  is the probability of occurrence of event $D$.

$P(E)$ is the probability of occurrence of event $E$.

For the specified values of $P(A)$, $P(B)$, $P(C)$, $P(D)$, and $P(E)$ and the calculated values of $P(X)$, $P(Y)$, and $P(Z)$, Equation (8.4) yields

$$P(T) = 1 - [1 - 0.02]^5 [1 - 0.0396] [1 - 0.0776] [1 - 0.0396],$$
$$= 0.2309.$$

Thus, the probability of the motor vehicle driver making an error is 0.2309.

## 8.5.2  Markov Method

The Markov method is named after its Russian originator, Andrei Andreyevich Markov (1856–1922) and is frequently used to conduct various types of reliability studies in the industrial sector; particularly when times to item/system failures and repair times are exponentially distributed. The method is described in detail in Chapter 5. The following example demonstrates its application to perform human error analysis in road transportation systems.

**Example 8.2**
After studying times to human error committed by motor vehicle drivers, it was concluded that they are exponentially distributed. More specifically, the error rate of motor vehicle drivers is constant.

Develop probability expressions that a motor vehicle driver will be performing his/her task successfully at time $t$ and not performing his/her task successfully at time $t$. Use the state space diagram shown in Figure 8.4 to develop these two expressions. The numerals in the diagram denote the motor vehicle driver states.
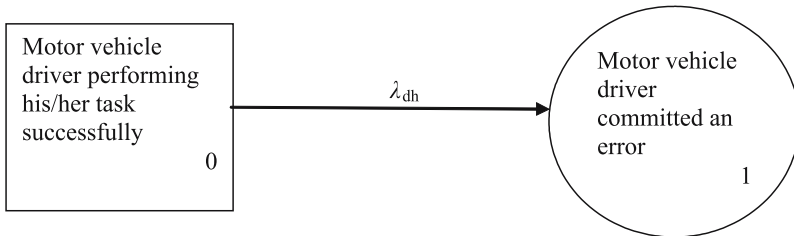


**Figure 8.4.** State space diagram representing the motor vehicle driver

Using the Markov method described in Chapter 5, we write down the following equations for the Figure 8.4:

$$P_0(t + \Delta t) = P_0(t)(1 - \lambda_{dh} \Delta t), \tag{8.1}$$

$$P_1(t + \Delta t) = P_1(t) + P_0(t) \lambda_{dh} \Delta t, \tag{8.2}$$

where

$t$          is time.

$\lambda_{dh}$       is the constant error rate of the motor vehicle driver.

$\lambda_{dh}\Delta t$     is the probability of human error by the motor vehicle driver in finite time interval $\Delta t$.

$P_0(t+\Delta t)$ is the probability that the motor vehicle driver is performing his/her task successfully (*i.e.*, State 0 in Figure 8.4) at time $(t+\Delta t)$.

$P_1(t+\Delta t)$ is the probability that the motor vehicle driver has committed an error (*i.e.*, State 1 in Figure 8.4) at time $(t+\Delta t)$.

$(1-\lambda_{dh}\Delta t)$ is the probability of zero human error by the motor vehicle driver in finite time interval $\Delta t$.

$P_0(t)$      is the probability that the motor vehicle driver is performing his/her task normally (*i.e.*, State 0 in Figure 8.4) at time $t$.

$P_1(t)$      is the probability that the motor vehicle driver has committed an error (*i.e.*, State 1 in Figure 8.4) at time $t$.

Rearranging Equations (8.1)–(8.2) and taking the limit as $\Delta t \to 0$, we get

$$\lim_{\Delta t \to 0} \frac{P_0(t+\Delta t)-P_0(t)}{\Delta t} = \frac{d P_0(t)}{dt} = -\lambda_{dh} P_0(t), \qquad (8.3)$$

and

$$\lim_{\Delta t \to 0} \frac{P_1(t+\Delta t)-P_1(t)}{\Delta t} = \frac{d P_1(t)}{dt} = \lambda_{dh} P_0(t). \qquad (8.4)$$

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

Solving Equations (8.3) and (8.4) by using Laplace transforms, we get

$$P_0(s) = \frac{1}{s+\lambda_{dh}}, \qquad (8.5)$$

and

$$P_1(s) = \frac{\lambda_{dh}}{s(s+\lambda_{dh})}, \qquad (8.6)$$

where

$s$ is the Laplace transform variable.

By taking the inverse Laplace transforms of Equations (8.5)–(8.6) yield

$$P_0(t) = e^{-\lambda_{dh} t}, \qquad (8.7)$$

$$P_1(t) = \left(1 - e^{-\lambda_{dh} t}\right). \qquad (8.8)$$

Thus, from Equation (8.7), the motor vehicle driver reliability, $R_d(t)$, at time $t$ is

$$R_d(t) = P_0(t) = e^{-\lambda_{dh} t}. \qquad (8.9)$$

Similarly, from Equation (8.8), the motor vehicle driver unreliability, $UR_d(t)$, at time $t$ is

$$UR_{\mathrm{d}}\left(t\right)=P_{1}\left(t\right)=1-\mathrm{e}^{-\lambda_{\mathrm{dh}}\,t}. \tag{8.10}$$

**Example 8.3**

Assume that the error rate of a motor vehicle driver is 0.005 errors/hour. Calculate the reliability of the motor vehicle driver during a 10-hour work period.

By substituting the specified data values into Equation (8.9), we get

$$R_{\mathrm{d}}\left(10\right)=\mathrm{e}^{-(0.005)\ (10)},$$
$$=0.9512.$$

Thus, the reliability of the motor vehicle driver is 0.9512.

## 8.6  Bus Accidents and Driver Error in Developing Countries

Each year, there are around 0.8 million road accident fatalities and 20–30 million road accident-related injuries throughout the world [2, 3]. As per References [2, 3], around 70% of these events occur in the developing countries. Furthermore, the fatality rate per registered vehicle is at least 10 to 20 times higher in the developing countries than the best industrialized countries. More specifically, the worst developing countries in the term of fatality rate are Central African Republic, Ethiopia, Tanzania, and Nepal [2, 3]. Fatality rates in these countries are 150–200 fatalities/10,000 vehicles/year, 150–200 fatalities/10,000 vehicles/year, 100–150 fatalities/10,000 vehicles/year, and 50–100 fatalities/10,000 vehicles/year, respectively.

For the period 1996–1998, bus accidents as percentage of total accidents and fatalities per bus accident are presented in Table 8.1 for five developing countries: Tanzania, Zimbabwe, Nepal, India, and Thailand [2, 3]. As per the table, the highest bus accidents as percentage of total accidents are in Tanzania, and the highest fatalities per bus accident are in Nepal. As per police analysis, the three main categories of causes for bus accidents in Tanzania were as follow [2, 3]:

- Human factors (76%)
- Vehicle condition (17%)
- External factors (7%)

The figure in parentheses in the above three categories denote their corresponding percentage. As per inputs from various sources including interviewees' perceptions, human errors were the principal contributory cause of bus or other road accidents in Tanzania.

Similarly, as per inputs from various sources, the likely causes of bus accidents in Nepal can be classified as follows [2, 18]:

- Drivers and driving habits
- Road condition
- Vehicle condition
- Other factors

**Table 8.2.** Bus accidents as percentage of total accidents and fatalities per bus accident in five developing countries

| No. | Country | Bus accidents as percentage of total accidents | Fatalities per bus accident |
|---|---|---|---|
| 1 | Tanzania | 24% | 0.39 |
| 2 | Zimbabwe | 15% | 0.02 |
| 3 | Nepal | 14% | 0.76 |
| 4 | India | 8% | 0.17 |
| 5 | Thailand | 5% | 0.34 |

As per Reference [2], 70–80% of bus accidents, for the period 1996–98, in Tanzania, Zimbabwe, Nepal, India, and Thailand were due to driver error. It simply means that human error is the single most important factor for the occurrence of bus accidents in these five countries.

## 8.7  Problems

1. Write an essay on human error in road transportation systems.
2. List at least seven facts and figures concerned with human error in road transportation systems.
3. Discuss operational influences that effect commercial motor vehicle driver performance.
4. Discuss four types of driver errors that can lead to an accident.
5. What are the most common driver errors?
6. Rank at least ten driver errors from highest frequency of occurrence to the lowest frequency of occurrence.
7. In fault tree in Figure 8.3, calculate the probability of the motor vehicle driver making an error if the occurrence probability of independent events shown in circles is 0.05. Single capital letters in the fault tree diagram denote corresponding events (*e.g.*, $T$: motor vehicle driver making an error).
8. Discuss the occurrence of bus accidents and driver error in developing countries.
9. Prove that the sum of Equations (8.5) and 8.6) is equal to $\dfrac{1}{s}$ and discuss what it means.

10. Assume that the constant error rate of a motor vehicle driver is 0.002 errors/ hour. Calculate reliability and unreliability of the motor vehicle driver during a 6-hour work period.

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# 9

# Human Error in Aviation

## 9.1 Introduction

Since the first aircraft flight made by the Wright brothers in 1903, the aviation industry has grown into billions of dollars of annual business throughout the world. In fact, as per the International Air Transport Association (IATA), over 1.6 billion passengers use the world's airlines for business and leisure travel each year, and over 40% of world trade of goods is carried by air [1]. Furthermore, in terms of employment air transport provides around 28 million jobs, directly or indirectly, worldwide.

Since the late 1950s, concerted efforts to reduce the accident rate in aviation have yielded unprecedented levels of safety. Today, the accident rate for air travel is one fatality per one million flights [1]. Although, the overall accident rate has declined considerably over the years, unfortunately reductions in human error-related accidents in aviation have failed to keep pace with the reduction of accidents due to environmental and mechanical factors [2–4]. In fact, humans have been an increasing causal factor in both military and civilian aviation accidents as mechanical equipment have become more reliable [2, 3]. Today, a very large percentage of all aviation accidents are attributable, directly or indirectly, to some form of human error.

This chapter presents various different aspects of human error in aviation.

## 9.2 Facts, Figures, and Examples

Some of the facts, figures, and examples, directly or indirectly, concerning human error in aviation are as follows:

- Each year over 1.6 billion passengers worldwide travel by air [1].
- As per a National Aeronautics and Space Administration (NASA) Study, over 70 percent of airline accidents, since the introduction of highly reliable turbojet aircraft in the late 1950s, involved some degree of human error [5].

- As per a Boeing study, the failure of the cockpit crew has been a contributing factor in over 73% of aircraft accidents globally [6, 7].
- As per a study reported in Reference [8], pilot error was responsible for 34% of major airline crashes between 1990 and 1996.
- In 1978, a United Airlines DC-8 aircraft carrying 189 people crashed while attempting to land in Portland, Oregan and killed ten of the people on board because of pilot error [5].
- A study of naval aviation accidents revealed that in 1977 accidents solely due to mechanical and environmental factors were almost equal to those, at least in part, to human error [2, 9]. However, by 1992 mechanical and environmental-related accidents were virtually eliminated, but the human-error related accidents were reduced by only 50% [2, 9].
- In 1982, an Air Florida Boeing 737 aircraft crashed into the Potomac River near Washington, D.C. because of its pilot's failure to heed the co-pilot's repeated warnings that the aircraft was moving too slowly during the acceleration prior to takeoff [5].
- As per a study reported in Reference [8], 45% of all major airline crashes occurring at airports are due to pilot error, in comparison to 28% of those occurring elsewhere.
- As per a scientific study of aviation crashes in the United States reported in Reference [8], crashes due to pilot error in major airlines are decreasing. More specifically, as per the findings, they decreased from 43% for the period 1983–1989 to 34% for the period 1990–1996.
- During the period 1983–1996, there were 29, 798 general aviation crashes, 371 major airline crashes, and 1,735 commuter/air taxi crashes [8]. A study of these crashes revealed that pilot error was a probable cause for 85% of general aviation crashes, 38% of major airline crashes, and 74% of commuter/air taxi crashes [8].

## 9.3  Organizational Factors in Commercial Aviation Accidents with Respect to Pilot Error

The occurrence of high-profile accidents such as the nuclear accident at Chernobyl [10], the piper Alpha oil platform explosion in the North Sea [11], and the Space Shuttle Challenger disaster [12] has brought considerable attention to the role of organizational factors in the causation of accidents in high-risk systems [13]. In recent years, considerable emphasis is being placed on organizational factors in aviation accidents with respect to pilot error. As the result of the emphasis, various studies have been conducted. One of these studies is reported in Reference [13]. This study analyzed the National Transportation Safety Board's (NTSB's) accident data concerning commercial aviation of the period 1990–2000. Sixty of the 1322 accidents that occurred during the specified period were attributable, directly or indirectly, to pilot error and contained 70 organizational causes. These causes or

factors were grouped under ten distinct categories. These categories, along with their corresponding brief descriptions in parentheses, are as follows [13]:

- Inadequate facilities (*i.e.*, failure to provide satisfactory lighting, environmental controls, clearance, *etc.* for flight operations)
- Inadequate procedures or directives (*i.e.*, conflicting or ill-defined policies, formal oversight of operation)
- Poor supervision of operations at management level (*i.e.*, failure to provide proper guidance, oversight, and leadership to flight operations)
- Faulty documentation (*i.e.*, incorrect checklists, signoffs, and record keeping that effects flight operations)
- Inadequate standards/requirements (*i.e.*, clearly defined organizational objectives and adherence to policy)
- Management/company induced pressures (*i.e.*, threats to pilot job status and/or pay)
- Poor initial, upgrade, or emergency training/transition (*i.e.*, opportunities for pilot training not implemented or made available to appropriate pilots)
- Insufficient or untimely information sharing (*i.e.*, logbooks, weather reports, and updates on the part of the organization)
- Poor surveillance of operations (*i.e.*, chain-of-command, organizational climate issues, and quality assurance and trend information)
- Poor substantiation process (*i.e.*, well-defined and verified process, accountability, standards of operation, regulation, and recording/reporting process)

The percentage contributions of the organizational causes or factors belonging to each of the above 10 categories to 60 accidents, were 1.5% (inadequate facilities), 21% (inadequate procedures or directives), 10% (poor supervision of operations at management level), 4% (faulty documentation), 12% (inadequate standards/requirements), 6% (management/company induced pressures), 18% (poor initial, upgrade, or emergency training/transition), 12% (insufficient or untimely information sharing), 13% (poor surveillance of operations), and 3% (poor substantiation process). It is to be noted from the above numerical values that 39% of the contribution was due to organization factors belonging to just two categories (*i.e.*, inadequate procedures or directives and poor surveillance of operations).

# 9.4  Factors Contributing to Flight Crew Decision Errors

There are various factors that can contribute to flight crew decision errors concerning incidents. In particular, at minimum the factors that must be assessed with respect to their significance in contributing to flight crew decision errors, are as follows [14]:

- Equipment factors. These include airplane flight deck indications, airplane con-figuration, and the role of automation.
- Crew factors. These include crew intention, crew coordination/communication, crew understanding of situation at the time of procedure execution, technical knowledge/experience/skills, factors that affect individual performance (*e.g.*, workload, fatigue, *etc.*), personal and corporate stressors, situation awareness factors (*e.g.*, vigilance, attention, *etc.*), and so on.
- Flight phase where error occurred.
- The procedure form which the error resulted. This includes crew interpretation of the relevant procedure, onboard source of the procedure, current guidelines and policies aimed at prevention of incident, procedure status, and procedural factors (*e.g.*, complexity, impracticality, negative transfer, *etc.* ).
- Environmental factors
- Other stimuli (*i.e.*, beyond indications)

## 9.5  Fatigue in Long-haul Operations

Pilot and other flight crew members' fatigue in long-haul flying is an important factor in the occurrence of human errors [15]. For example, each month National Aeronautics and Space Administration's (NASA's) Aviation Safety Reporting System (ASRS) receives reports from various long-haul flight crew members of how fatigue and sleep loss have been contributors to major operation-associated errors such as listed below [15]:

- Landing with proper clearance
- Altitude busts
- Improper fuel calculations
- Track deviations

As per Reference [16], the sleep loss along with jet lag associated with multiple time zone flights contribute to about three-times higher loss ratio for long-haul wide-body aircraft operations, in comparison to the combined short and medium-range fleet operations.

Three underlying factors for increased fatigue due to jet lag that can interfere with flight crew performance and judgment in the cockpit are shown in Figure 9.1 [15]. The factor, disruption of circadian, or 24-hour, rhythms in physiological and psychological functions, is probably best known by aviators as the major cause of jet lag. It occurs because of the slow rate at which physiological processes underlying both sleep and wake adjust to rather rapid changes in time. It is to be noted that a clock delay occurs on flights in westward direction, as opposed to a clock advance on flights in eastward direction. Past experiences indicate that the latter is frequently more difficult to adjust than the former.
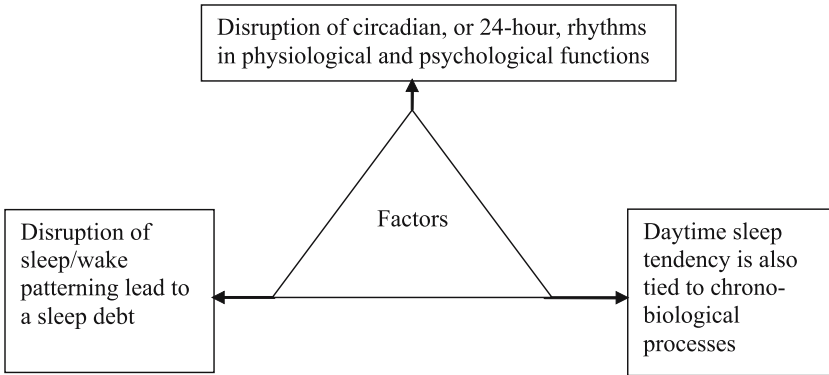
**Figure 9.1.** Factors/causes for increased fatigue due to jet lag

The factor, disruption of sleep/wake patterning leading to a sleep debt, simply means that the circadian disruption generated by Trans-meridian flight normally leads to sleep loss that further increases fatigue quite significantly. Sleep duration is longest when one goes to bed near the daily temperature peak (*i.e.*, early evening) and shortest when one goes to bed near the daily trough (*i.e.*, around 4:00 a.m.). All in all, sleep loss is a major operational variable in cockpit fatigue.

The factor, daytime sleep tendency is also tied to chrono-biological processes, simply means that not only is sleep during long-haul operational schedules affected by the biological clock and sleep loss, but ones level of alertness during awake is also influenced quite significantly by biological clock dynamics.

Finally, from the above three factors, one can conclude the following:

- Sleepiness is rhythmic that reaches a peak value in the early morning and late afternoon hours.
- An individual's internal body clock has a period greater than 24 hours.
- The sleep length and type is partially determined by biological clocks.

# 9.6  Reasons for Retaining Air Traffic Controllers, Effects of Automation on Controllers, and Factors for Controller-caused Airspace Incidents

There are many reasons for retaining air traffic controllers. Some of the most commonly cited reasons for the retention of human controllers, even in highly automated air traffic control systems, are as follows [17]:

- To understand and interpret the automation
- To retain human legal responsibility
- To deal with emergency and non-standard situations
- To maintain human knowledge and skills

- To revert to manual mode in the event of equipment failure
- To conduct training or assessments
- To respond to different machine modes
- To retain human intentionality

Although air traffic controllers are still present, in the future, automation may change human tasks and functions to a such degree that may make it appropriate to rematch humans and machines before accruing any benefits from it. More specifically, automated aids for human higher cognitive functions definitely need more in human factors terms than proof that they are reliable, safe, and efficient and can help or increase human performance. Nonetheless, some of the incidental effects of automation on air traffic controllers are as follows [17]:

- Automation can undermine the trust of controllers in the machine unless it is highly reliable and safe.
- Automation can affect the formation and maintenance of situational awareness of controllers in the form of the mental picture, concerning the existing and potential air traffic scenario.

**Table 9.1.** Factors for controller-caused airspace incidents grouped under three categories

| No. | Type of incident | Factors | | |
|-----|------------------|---------|---|---|
| | | Category I: Active | Category II: Organization | Category III: Local |
| 1 | Near collision | Diagnosis, procedural, and actions inconsistent with specified procedures | Poor defenses and inadequate resource management | Various psychological factors |
| 2 | Loss of separation | Actions incompatible with specified procedures (*i.e.*, execution errors) | Poor control and monitoring, poor specifications or requirements | High controller workload factors in addition to poor concentration/lack of attention |
| 3 | Air traffic service (ATS) flight information deficiency | Inaccurate system "diagnosis" errors | Inadequate procedures and poor control and monitoring | Inadequate checking and inadequate concentration/lack of attention |
| 4 | ATS coordination deficiency | Actions incompatible with specified procedures (*i.e.*, execution errors) | Deficiencies in system design and poor specifications or requirements | Poor concentration, instructions and procedures |
| 5 | ATS clearance deficiency | Actions incompatible with specified procedures | Poor control and monitoring and poor resource management instructions | Poor checking and concentration and lack of attention |

- Automation can cause human error, particularly if it requires new controller knowledge and new operational procedures, when there is not adequate transfer of training between the old system and the new system.
- Automation can induce controller uncertainty about detecting any machine fault, finding the degree of its ramifications, and determining which of the machine functions remain reasonably unaffected by it.

There are many factors for controller-caused airspace incidents. A number of such factors, revealed by a New Zealand study of controller caused airspace incidents between 1994–2002, are presented in Table 9.1 under three distinct categories [18]. These categories are active, local, and organization.

## 9.7 Types of Pilot–Controller Communication Errors and Recommendations to Reduce Communication Errors

The communication between pilots and air traffic controllers is subject to various types of errors. A Federal Aviation Administration (FAA) study analyzed a total of 386 reports submitted to the Aviation Safety Reporting System (ASRS) between July 1991 and May 1996. As per this study, the communication errors can be grouped into four types as shown in Figure 9.2 [19]. These are read-back/hear-back errors, no pilot readback, hearback errors Type I, and miscellaneous errors. A read-back error may simply be described as a discrepancy between the clearance the air traffic controller issued and the pilot read-back. In situations when the controller overlooks to correct this discrepancy, the oversight is know as "hear-back error".
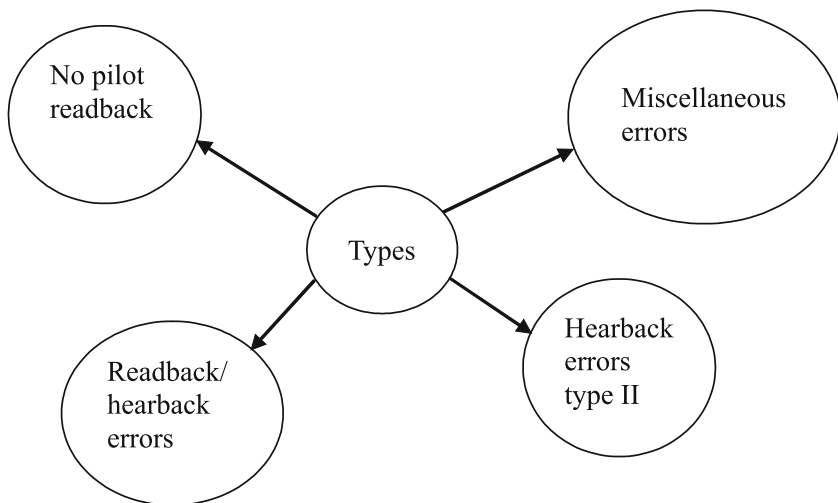


**Figure 9.2.** Types of pilot-controller communication errors

In this study, read-back/hear-back errors were the most common type of communication errors and they accounted for 47% of the total errors. The most common contributing factor for the occurrence of readback/hearback errors was similar call signs, followed by controller workload [19].

A pilot read-back is probably the first and most efficient way to catch miscommunications between pilots and controllers. In this study, a lack of a pilot readback (*i.e.*, no pilot readback) accounted for 25% of the total errors. The pilot expectation was the most common factor associated with a no pilot read-back that resulted in communication errors [19].

Hear-back errors type II are controller errors in which the aircraft pilot correctly and accurately repeats the issued clearance, but the controller overlooks to notice the issued clearance that, in fact, was not the clearance that he/she intended to issue. This type of error also includes events where the pilot made an action statement or intent that the controller should have picked up was, in fact, problematic. In this study, hear-back errors type II accounted for 18% of the total errors [19].

Miscellaneous errors are all those errors that cannot be classified under the above three types of errors. An example of such errors is a pilot misunderstanding a clearance. In this study, miscellaneous errors accounted for 10% of the total errors [19].

Some of the recommendations that can help to reduce communication errors between pilots and controllers are as follows [19]:

- Encourage air traffic controllers to speak slowly and distinctly.
- Encourage aircraft pilots to respond to controller instructions with a full readback of all important elements.
- In the event of having similar call signs on the frequency, encourage controllers to continue to announce this fact.
- Encourage controllers not to issue "strings" of instructions to different aircraft.
- Encourage controllers to keep all instructions short with a maximum of four instructions per transmission.
- In the event of having similar call signs on the frequency, encourage all pilots to say their call sign prior and after each and every readback.
- Encourage controllers to treat all readbacks as they would treat any other piece of incoming information.

## 9.8  Methods for Performing Human Error Analysis in Aviation

There are many methods and techniques developed in areas such as reliability, quality, and safety for performing various types of analysis [2, 20, 21]. Some of these methods and techniques can also be used to perform human error analysis in aviation. These methods and techniques include fault tree analysis, cause and effect

diagram, failure modes and effect analysis, Markov method, Pareto diagram and the human factors analysis and classification systems. One of these methods and techniques (*i.e.*, fault tree analysis) is presented below.

## 9.8.1  Fault Tree Analysis

This is a widely use method for performing reliability and safety analyses in the industrial sector and it was developed in the early 1960s at the Bell Telephone Laboratories [22]. The method is described in Chapter 5, and its application to perform human error analysis in aviation is demonstrated by the following example.

**Example 9.1**
Assume that a pilot can commit an error due to any of three causes: carelessness, faulty communication with air traffic controllers, or faulty information from co-pilot. In turn, faulty communication with air traffic controllers could either be caused by poor communication channels or language barrier. In addition, two causes for receiving faulty information from co-pilot are faulty documentation or co-pilot carelessness.

   Develop a fault tree for the top event, pilot committing an error, by using fault tree symbols given in Chapter 5. Using fault tree symbols given in Chapter 5, a fault tree for the example, shown in Figure 9.3, was developed.
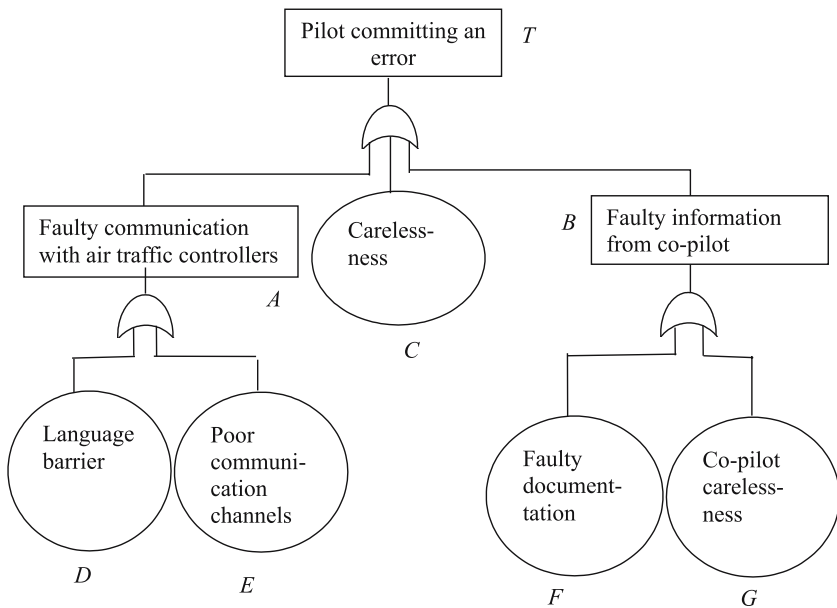


**Figure 9.3.** A fault tree for Example 9.1

**Example 9.2**

In Figure 9.3 fault tree, calculate the probability of occurrence of the top event: pilot committing an error, if the occurrence probability of independent fault events denoted by circles is 0.05. Single capital letters in the fault tree diagram denote corresponding fault events (*e.g.*, *F*: Faulty documentation and *T*: Pilot committing an error).

Thus from Chapters 2, 5 and Reference [20] the probability of occurrence of event A is

$$P(A) = 1 - [1 - P(D)][1 - P(E)], \tag{9.1}$$

where,

$P(D)$ is the probability of occurrence of event $D$.
$P(E)$ is the probability of occurrence of event $E$.

For the specified values of $P(D)$ and $P(E)$, Equation (9.1) yields

$$P(A) = 1 - [1 - 0.05][1 - 0.05],$$
$$= 0.0975.$$

Similarly, the probability of occurrence of event B is given by

$$P(B) = 1 - [1 - P(F)][1 - P(G)], \tag{9.2}$$

where,

$P(F)$ is the probability of occurrence of event $F$.
$P(G)$ is the probability of occurrence of event $G$.

For the specified values of $P(F)$ and $P(G)$, from Equation (9.2), we get

$$P(B) = 1 - [1 - 0.05][1 - 0.05],$$
$$= 0.0975.$$

Finally, the probability of occurrence of top event $T$ (*i.e.*, pilot committing an error) is

$$P(T) = 1 - [1 - P(A)][1 - P(B)][1 - P(C)], \tag{9.3}$$

where,

$P(C)$ is the probability of occurrence of event $C$.

For the calculated values of $P(A)$ and $P(B)$ and the specified value of $P(C)$, Equation (9.3) yields

$$P(T) = 1 - [1 - 0.0975][1 - 0.0975][1 - 0.05],$$
$$= 0.2262.$$

Thus, the probability of occurrence of the top event $T$: Pilot committing an error is 0.2262. Figure 9.4 shows the redrawn fault tree of Figure 9.3 with the given and calculated fault event occurrence probability values.
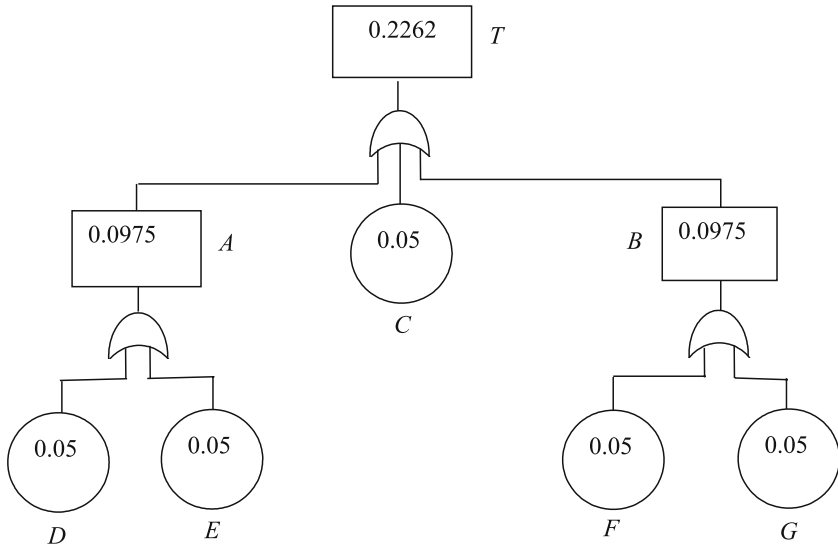
**Figure 9.4.** Redrawn Figure 9.3 fault tree with the calculated and specified fault event occurrence probability values

## 9.9 Examples and Study of Actual Airline Accidents due to Human Error

Over the years many airline accidents have occurred, directly or indirectly, due to human error. Two of these accidents were as follows [2]:

- **Korean Airlines Flight KAL007 Accident.** A Korean Airlines aircraft carrying 246 passengers and 23 crew members on board, took off from Anchorage, Alaska en route to Seoul, South Korea on August 31, 1983. The plane gradually drafted off course into Soviet territory and was shot down by two heat-seeking missiles fired from a Soviet fighter plane. As the result of this international incident all people on board the aircraft died.
  A subsequent investigation by the International Civil Aviation Organization (ICAO) revealed that this tragedy or accident was due to pilot error [2, 22]. More specifically, flight crew failed to detect the aircraft's deviation from its preassigned flight track for over five hours because of a lack of situational awareness and poor flight deck co-ordination [22].
- **British Midland Airways Flight BD092 Accident.** A British Midland Airways twin-engine aircraft Boeing 737-400 departed from Heathrow Airport, London, U.K. for Belfast, Northern Ireland on January 8, 1989 and crashed due to engine-related problems. A total of 39 people lost their lives in the crash [2]. A subsequent investigation revealed that the aircraft's pilot failed to identify correctly the engine that had malfunctioned [23].

## 9.10  Accident Prevention Strategies

Over the years various strategies have been explored or proposed to minimize the occurrence of aircraft accidents. A careful attention to factors such as listed below can be quite useful to prevent aircraft accidents [14, 24].

- Flying pilot adherence to procedures
- Non-flying pilot adherence to procedures
- Other operational procedural considerations
- Maintenance/inspection action
- Design improvement
- Air traffic control-crew communication
- Embedded piloting skills
- Air traffic control system performance
- Approach path stability
- Pilot experience in aircraft type
- Captain/instructor pilot exercise of authority
- Elimination of runway hazards
- Control of crew fatigue
- First officer's cross-check performance as non-flying pilot
- Response to ground proximity warning system (GPWS)
- Weather information availability and accuracy
- Flight engineer adherence to procedures
- Flying pilot awareness and attention
- Go-around decision
- Use of all available approach aids
- Training for abnormal conditions

## 9.11  Problems

1. Write an essay on human error in aviation industry.
2. List at least six facts and figures concerned with human error in aviation.
3. Discuss organizational factors in commercial aviation accidents with respect to pilot error.
4. List at least five important factors that must be assessed with respect to their significance in contributing to flight crew decision errors.
5. Discuss factors/causes for increased flight crew fatigue due to jet lag.
6. What are the important reasons for retaining air traffic controllers, even in highly automated air traffic control systems?
7. Discuss incidental effects of automation on air traffic controllers.

8.  Discuss four types of pilot-controller communication errors.

9.  List at least five most important ways for reducing communication errors between pilots and controllers.

10. Discuss the following two aircraft accidents:
    - Korean Airlines flight KAL007 accident
    - British Midland Airways Flight BD092 accident

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# 10

# Human Error in Aircraft Maintenance

## 10.1 Introduction

Aircraft maintenance is an important element of the aviation system that supports aviation industry worldwide. As per References [1, 2], in 1989 the maintenance element constituted around 12% of US airlines' operating costs, or more than $8 billion annually. Needless to say, growth in air traffic and increased demands upon aircraft utilization due to the stringent requirements of commercial schedules continue to put pressures on maintenance operations for on-time performance. This, in turn, has opened up further windows of opportunity for the occurrence of human errors [3].

Thus, for a safe and reliable air transportation system, the existence of a sound aircraft maintenance system is essential [4]. The backbone of this system is the aircraft maintenance technician (AMT) workforce. This workforce looks after needs and requirements of maintaining aircraft for safe and operationally efficient flights. Just like in the performance of any other task, the performance of aircraft maintenance tasks is subject to human error. Past experiences indicate that human error in aircraft maintenance has been a causal factor in several air carrier accidents around the world that have resulted in many fatalities [3]. It means that there is a definite need to minimize the occurrence of such errors for safe and reliable flights. This chapter presents various important aspects of human error in aircraft maintenance.

## 10.2 Facts, Figures and Examples

Some of the facts, figures, and examples, directly or indirectly, concerned with human error in aircraft maintenance are as follows:

- As per References [5, 6], maintenance and inspection have been found to be factors in around 12% of major aircraft accidents.
- In 1979, in a DC-10 aircraft accident due to improper maintenance procedures followed by maintenance personnel 272 people died [7].

- A study of safety issues versus onboard fatality of worldwide jet fleet for the period 1982–1991 singled out maintenance and inspection as the second most important safety issue with onboard fatalities [8, 9].
- In 1983, an aircraft departing from Miami Airport lost oil pressure in all three of its engines because of missing chip detector O-rings. A subsequent investigation of the incident revealed that poor inspection and supply procedures were the cause of the problem [10].
- A study reported that 18% of all aircraft accidents are maintenance related [4, 11].
- In 1986, a report stated that mechanical failure preceded by faulty maintenance is the major cause of aircraft accidents [12, 13].
- A study reported that 15% of aircraft accidents during the period 1982–1991 had maintenance as a contributing factor [14].
- A study reported that the distribution of 122 maintenance errors in a major airline over a period of three years was: omission (56%), incorrect installations (30%), wrong parts (8%), and other (6%) [15, 16].
- A study of data obtained from the United Kingdom Civil Aviation Authority Mandatory Occurrence Report database revealed that maintenance error events per million flights almost doubled over the period 1990–2000 [17].
- In 1988, the upper cabin structure of a Boeing 737 -200 aircraft was ripped away during a flight because of structural failure. A subsequent investigation revealed that two maintenance inspectors failed to identify over 240 cracks in the skin of the aircraft at the time of inspection [17, 18].
- In 1991, an Embraer 120 aircraft carrying 13 people on board experienced a sudden structural break-up in flight and crashed, killing all on board. A subsequent investigation into the crash revealed that the cause of the accident was the removal of attaching screws, on the top of the left side leading edge of the horizontal stabilizer, during scheduled maintenance [3, 17].

## 10.3  Reasons for the Occurrence of Human Error in Maintenance

There are virtually limitless factors that can impact worker performance. The International Civil Aviation Organization (ICAO) lists over 300 such factors/influences ranging from temperature to boredom [19]. Nonetheless, some of the important reasons for the occurrence of human error in maintenance are as follows [7, 20]:

- Complex maintenance-related tasks
- Poor work environment (*i.e.*, lighting, humidity, temperature, *etc.*) and work layout
- Time pressure
- Fatigued maintenance personnel
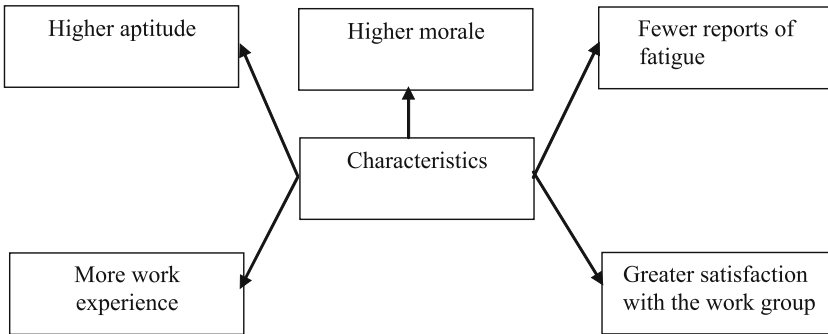- Inadequate work tools, training, and experience

**Figure 10.1.** Highest ranked maintenance technicians' characteristics

- Poor equipment design
- Poorly written maintenance procedures
- Outdated maintenance manuals

In particular, with respect to maintenance technicians' training and experience, as per a study, those who ranked highest possessed characteristics such as shown in Figure 10.1 [7, 21]. Also, as per correlation analysis there were positive correlations between task performance and factors such as years of work experience, morale, responsibility-handling ability, and amount of time in career field. Similarly, there were negative correlations between task performance and anxiety level and fatigue symptoms.

## 10.4  Major Categories of Human Errors in Aircraft Maintenance and Inspection Tasks, Classification of Human Error in Aircraft Maintenance and Their Occurrence Frequency, and Common Errors in Aircraft Maintenance

A study of a major United States Airlines data indicates that there are many major categories of human errors in aircraft maintenance and inspection tasks. Eight of these categories are shown in Figure 10.2 [16, 22].

A Boeing study examined 86 aircraft incident reports concerning maintenance error and classified human errors into 31 distinct categories. These categories along with their occurrence frequency are presented in Table 10.1 [23].

A United Kingdom Civilian Aviation Authority (UKCAA) study conducted over a period of three years, reported the following commonly occurring human errors in aircraft maintenance [14, 16]:

- Wrong installation of parts
- Loose objects such as tools left in the aircraft

- Failure to remove landing gear ground lock pins prior to aircraft departure
- Fitting of incorrect components or parts
- Unsecured fuel caps and refuel panels
- Discrepancies in electrical wiring including cross connections
- Unsecured fairings, cowlings, and access panels
- Inadequate lubrication

**Table 10.1.** Maintenance error categories along with their corresponding occurrence frequencies

| No. | Maintenance error category | Occurrence frequency |
|---|---|---|
| 1 | System operated in unsafe conditions | 16 |
| 2 | System not made safe | 10 |
| 3 | Equipment failure | 10 |
| 4 | Towing event | 10 |
| 5 | Falls and spontaneous actions | 6 |
| 6 | Degradation not discovered | 6 |
| 7 | Person entered dangerous zones | 5 |
| 8 | Unfinished installation | 5 |
| 9 | Work not documented | 5 |
| 10 | Did not obtain or use appropriate equipment | 4 |
| 11 | Person contacted hazard | 4 |
| 12 | Unserviceable equipment/system used | 4 |
| 13 | System/equipment not activated/deactivated | 4 |
| 14 | No appropriate verbal warning given | 3 |
| 15 | Safety lock or warning moved | 2 |
| 16 | Pin/tie left in place | 2 |
| 17 | Not tested appropriately | 2 |
| 18 | Equipment/vehicle contacted aircraft | 2 |
| 19 | Warning sign or tag not used | 2 |
| 20 | Vehicle driving instead of towing | 2 |
| 21 | Incorrect fluid type | 1 |
| 22 | Access panel not closed | 1 |
| 23 | Incorrect panel installation | 1 |
| 24 | Material left in engine/aircraft | 1 |
| 25 | Wrong orientation | 1 |
| 26 | Equipment not installed | 1 |
| 27 | Contamination of open system | 1 |
| 28 | Incorrect component/equipment installed | 1 |
| 29 | Unable to access part or component in stores | 1 |
| 30 | Necessary servicing not performed | 1 |
| 31 | Miscellaneous | 6 |
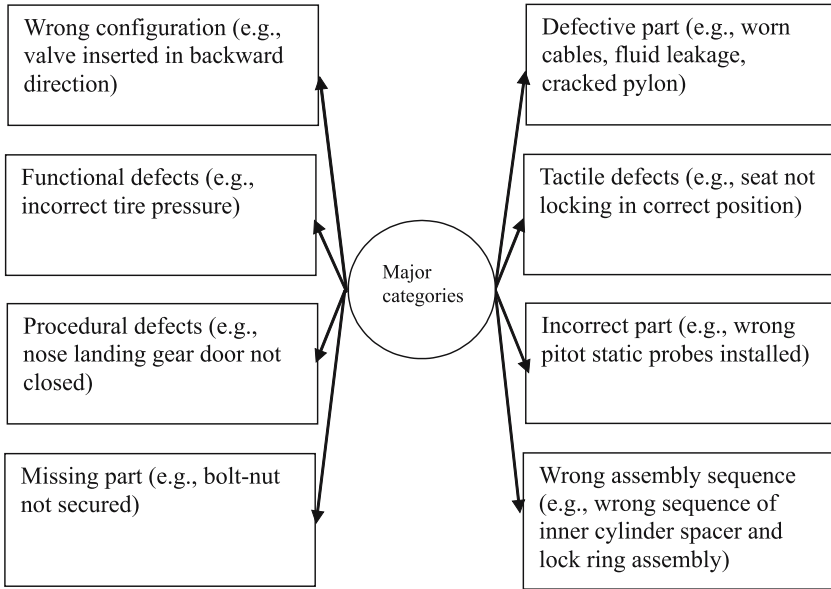
**Figure 10.2.** Major categories of human errors in aircraft maintenance and inspection tasks

# 10.5  Methods for Performing Human Error Analysis in Aircraft Maintenance

Over the years many methods have been developed to perform various types of reliability analysis in engineering systems. Two widely used methods are fault tree analysis (FTA) and the Markov method. Both these methods can also be used to perform human error analysis in aircraft maintenance. Their applications to perform human error analysis in aircraft maintenance are presented below, separately.

## 10.5.1  Fault Tree Analysis

This method is widely used in the industrial sector to perform various types of reliability and safety studies. Additional information on the method is available in Chapter 5 and References [20, 24]. The following example demonstrates its application in performing human error analysis in aircraft maintenance.

**Example 10.1**

Assume that the causes for an aircraft maintenance technician making an error are time pressure, poor management, inadequate tools, poorly written maintenance manuals, poor training, or use of incorrect maintenance manual. In turn, two factors for the time pressure are emergency job or management requirement. Similarly, two

reasons for the poor management are poor supervisory staff or poor organizational structure.

Develop a fault tree for the top event, aircraft maintenance technician making an error, by using the Chapter 5 fault tree symbols. Thus, by using fault tree symbols given in Chapter 5, a fault tree for the example was developed and is shown in Figure 10.3.

## Example 10.2

Assume that the occurrence probability of independent fault events denoted by circles in Figure 10.3 is 0.01. Calculate the probability of occurrence of the fault tree top event: aircraft technician making an error. Single capital letters in the fault tree diagram denote corresponding fault events (*e.g.*, $K$: Poor training and $L$: Inadequate tools).

Thus, from Chapter 5 and Reference [20] the probability of occurrence of event $X$ is

$$P(X)=1-\left[1-P(M)\right]\left[1-P(N)\right], \tag{10.1}$$

where
$P(M)$ is the probability of occurrence of event $M$.
$P(N)$ is the probability of occurrence of event $N$.

Using the specified value of $P(M)=P(N)=0.01$ in Equation (10.1), we get

$$P(X)=1-\left[1-0.01\right]\left[1-0.01\right],$$
$$= 0.0199.$$
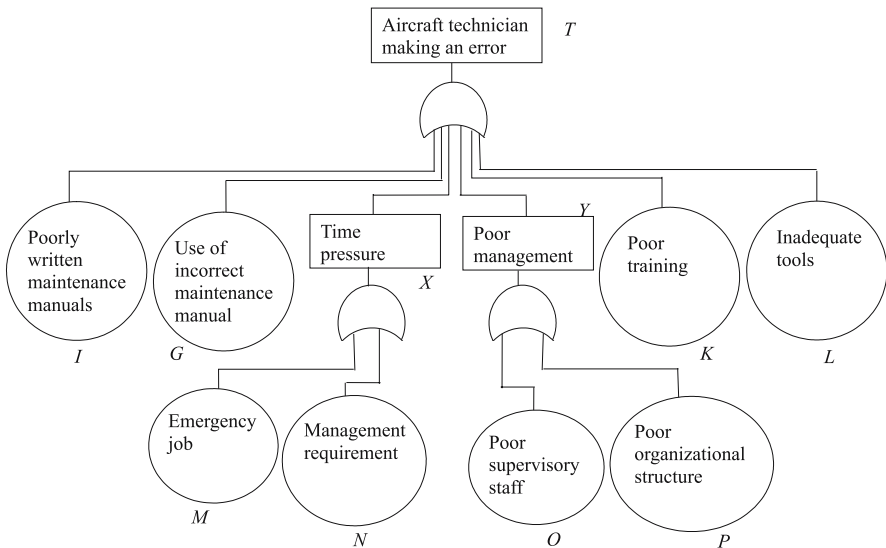


**Figure 10.3.** Fault tree for Example 10.1

Similarly, the probability of occurrence of event $Y$ is given by

$$P(Y)=1-\left[1-P(O)\right]\left[1-P(P)\right], \tag{10.2}$$

where
$P(O)$ is the probability of occurrence of event $O$.
$P(P)$ is the probability of occurrence of event $P$.

Using the given value of $P(O)=P(P)=0.01$ in Equation (10.2) yields

$$P(Y)=1-\left[1-0.1\right]^{2},$$
$$=0.0199.$$

Finally, the probability of occurrence of the fault tree top event $T$ is

$$P(T)=1-\left[1-P(X)\right]\left[1-P(Y)\right]\left[1-P(I)\right]\left[1-P(G)\right]\left[1-P(K)\right]\left[1-P(L)\right], \tag{10.3}$$

where
$P(I)$  is the probability of occurrence of event $I$.
$P(G)$ is the probability of occurrence of event $G$.
$P(K)$ is the probability of occurrence of event $K$.
$P(L)$  is the probability of occurrence of event $L$.
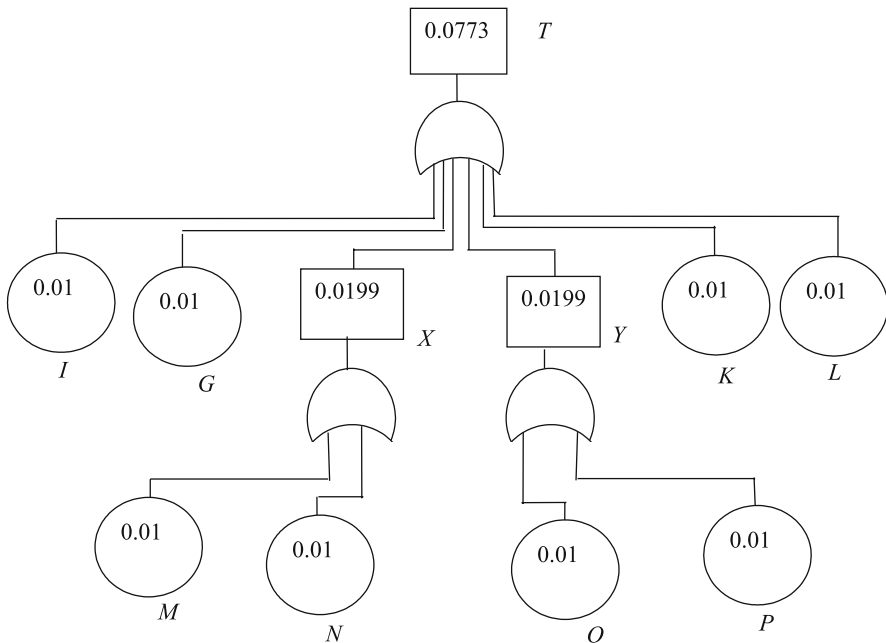


**Figure 10.4.** Redrawn fault tree of Figure 10.3 with the specified and calculated event occurrence probability values

Using the above calculated values and the specified data values in Equation (10.3), we get

$$P(T)=1-[1-0.0199]^2[1-0.01]^4,$$
$$=0.0773.$$

Thus, the probability of occurrence of the fault tree top event: aircraft technician making an error, is 0.0773. Figure 10.4 shows the Figure 10.3 fault tree with the above calculated and the specified event occurrence probability values.

## 10.5.2  Markov Method

This is a widely used method to perform various types of reliability analysis and is named after a Russian mathematician, its originator. Additional information on the method is available in Chapter 5 and in References [20, 24]. Its application to perform human error analysis in aircraft maintenance is demonstrated through the following example:

**Example 10.3**
Assume that an aircraft engine can fail either due to a maintenance error or other than a maintenance error. Maintenance error and non-maintenance error failure rates are constant. The failed engine from both the failure modes is repaired at a constant rate. This scenario is depicted by the state space diagram shown in Figure 10.5. Numerals in circles denote system states.

Develop probability expressions for the aircraft engine working normally, failed due to a maintenance error, and failed due to a non-maintenance error failure at time t, by using the Markov method.
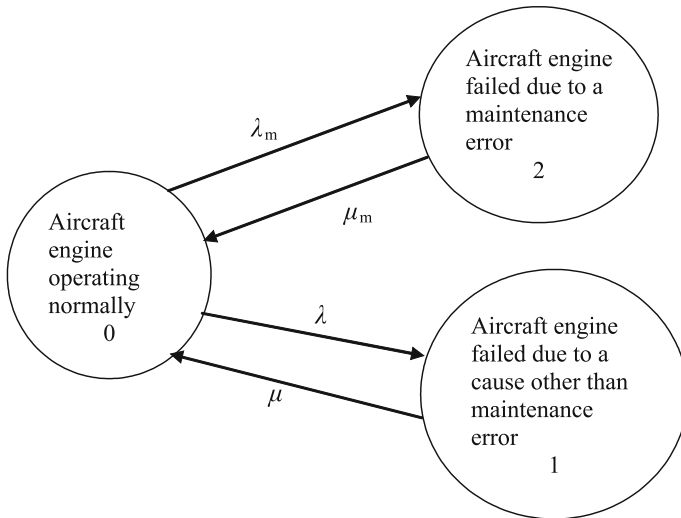


**Figure 10.5.** Aircraft engine with maintenance error transition diagram

With the aid of Markov method, we write down the following Equations for the Figure 10.5 diagram:

$$\frac{dP_0(t)}{dt} + (\lambda + \lambda_m) P_0(t) = \mu_m P_2(t) + \mu P_1(t), \tag{10.4}$$

$$\frac{dP_1(t)}{dt} + \mu P_1(t) = \lambda P_0(t), \tag{10.5}$$

$$\frac{dP_2(t)}{dt} + \mu_m P_2(t) = \lambda_m P_0(t). \tag{10.6}$$

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

Symbols used in Equations (10.4)–(10.6) and Figure 10.5 are defined below.

$t$      is time.

$P_i(t)$    is the probability that the aircraft engine is in state $i$ at time $t$; for $i = 0$ means the engine operating normally, $i = 1$ means the engine failed due to a cause other than maintenance error, $i = 2$ means the engine failed due to a maintenance error.

$\lambda$      is the aircraft engine constant non-maintenance error failure rate.

$\lambda_m$    is the aircraft engine constant maintenance error rate.

$\mu$      is the aircraft engine constant repair rate from state 1.

$\mu_m$    is the aircraft engine constant repair rate from state 2.

Solving Equations (10.4)–(10.6) by using Laplace transforms, we get

$$P_0(s) = \frac{(s + \mu)(s + \mu_m)}{A}, \tag{10.7}$$

where

$s$ is the Laplace transform variable and

$$A = s \left[ s^2 + s \left( \mu + \mu_m + \lambda + \lambda_m \right) + \left( \mu \mu_m + \lambda \mu_m + \lambda_m \mu \right) \right], \tag{10.8}$$

$$P_1(s) = \frac{\lambda (s + \mu_m)}{A}, \tag{10.9}$$

$$P_2(s) = \frac{\lambda_m (s + \mu)}{A}. \tag{10.10}$$

By taking inverse Laplace transforms of Equations (10.7)–(10.10), we get

$$P_0(t) = \frac{\mu \mu_m}{c_1 c_2} + \left\{ \frac{(c_1 + \mu_m)(c_2 + \mu)}{c_1 (c_1 - c_2)} \right\} e^{c_1 t} - \left\{ \frac{(c_2 + \mu)(c_2 + \mu_m)}{c_1 (c_1 - c_2)} \right\} e^{c_2 t}, \tag{10.11}$$

where

$$c_1, c_2 = \frac{-(\mu + \mu_m + \lambda + \lambda_m) \pm \left[ (\mu + \mu_m + \lambda + \lambda_m)^2 - 4 (\mu \mu_m + \lambda \mu_m + \lambda_m \mu) \right]^{1/2}}{2},$$

$$\tag{10.12}$$

$$c_1 c_2 = \mu\,\mu_{\mathrm{m}} + \lambda\,\mu_{\mathrm{m}} + \lambda_{\mathrm{m}}\,\mu, \tag{10.13}$$

$$c_1 + c_2 = -\left(\mu + \mu_{\mathrm{m}} + \lambda + \lambda_{\mathrm{m}}\right), \tag{10.14}$$

$$P_1(t) = \frac{\lambda\,\mu_{\mathrm{m}}}{c_1 c_2} + \left\{\frac{\lambda c_1 + \lambda\,\mu_{\mathrm{m}}}{c_1 (c_1 - c_2)}\right\} e^{c_1 t} - \left\{\frac{(\mu_{\mathrm{m}} + c_2)\lambda}{c_2 (c_1 - c_2)}\right\} e^{c_2 t}, \tag{10.15}$$

$$P_2(t) = \frac{\lambda_{\mathrm{m}}\,\mu}{c_1 c_2} + \left\{\frac{\lambda_{\mathrm{m}} c_1 + \lambda_{\mathrm{m}}\,\mu}{c_1 (c_1 - c_2)}\right\} e^{c_1 t} - \left\{\frac{(\mu + c_2)\lambda_{\mathrm{m}}}{c_2 (c_1 - c_2)}\right\} e^{c_2 t}. \tag{10.16}$$

The probability of the aircraft engine failure due to maintenance error at time $t$ is given by Equation (10.16).

As $t$ becomes very large, Equation (10.16) reduces to

$$P_2 = \frac{\lambda_{\mathrm{m}}\,\mu}{c_1 c_2},$$

$$= \frac{\lambda_{\mathrm{m}}\,\mu}{\mu\,\mu_{\mathrm{m}} + \lambda\,\mu_{\mathrm{m}} + \lambda_{\mathrm{m}}\,\mu}. \tag{10.17}$$

where

$P_2$    is the steady state probability of the aircraft engine failure due to maintenance error.

## Example 10.4

Assume that the constant failure rate of an aircraft engine due to maintenance error is 0.0001 failures/hour and the engine constant failure rate other than due to maintenance error is 0.0009 failures/hour. The engine constant repair rate is 0.004 repairs/hour. More specifically, it is same for the both types of failures.

Calculate the steady state probability of the engine failure due to maintenance error. Thus, by substituting the given data values into Equation (10.17), we get

$$P_2 = \frac{(0.0001)(0.004)}{(0.004)^2 + (0.0009)(0.004) + (0.0001)(0.004)},$$

$$= 0.02.$$

Thus, the steady state probability of the aircraft engine failure due to maintenance error is 0.02.

# 10.6  Case Studies of Human Error in Aviation Maintenance

Over the years, many aircraft accidents due to human error in maintenance have occurred. Two of these accidents are briefly described below.

### 10.6.1 British Airways BAC 1–11 Aircraft Accident

This accident occurred on June 10, 1990 when a British Airways BAC 1–11 aircraft departed Birmingham International airport in the United Kingdom for Malaga, Spain with 81 passengers and 6 crew members on board. As the aircraft was climbing through 17,300 feet pressure altitude, a cockpit windscreen blown out and sucked out the pilot in command through the windscreen aperture [3].

Fortunately, the co-pilot immediately regained control of the aircraft and the cabin crew members held the pilot by the ankles until the landing of the aircraft. A subsequent investigation into the accident revealed that the cause of the accident was the fitting of a replacement windscreen by using incorrect bolts [3].

### 10.6.2 Continental Express Embraer Brasilia Accident

This accident occurred in September 1991 when a Continental Express Embraer Brasilia crashed, killing all on board, because the leading edge of the left horizontal stabilizer separated from the aircraft [2]. A subsequent investigation into the accident revealed that the night before the accident some maintenance work, involving the removal of screws from the upper left surface of the aircraft's "T-tail," was performed. When the shift change occurred, the work was only partially completed and it was not documented.

Unfortunately, maintenance technicians of the incoming shift, being unaware of the partial completion of the maintenance work, signed the aircraft back into service. In the final report on the accident, the National Transportation Safety Board highlighted deficient maintenance practices within the airline organization [2, 25].

## 10.7 Useful Guidelines to Reduce Human Error in Aircraft Maintenance

Over the years, various guidelines have been developed to reduce the occurrence of human error in aircraft maintenance. These guidelines cover the following ten areas [9]:

- Tools and equipment
- Procedures
- Design
- Human error risk management
- Towing aircraft
- Maintenance incident feedback
- Training
- Shift handover
- Communication
- Supervision

Guidelines associated with each of the above ten areas are presented below, separately. Two guidelines concerning tools and equipment are reviewing systems by which items such as stands and lighting systems are kept to remove unserviceable equipment from service and repairing it rapidly, and ensuring the storage of lock-out devices in such a way that it becomes immediately apparent when they are left in place inadvertently. Four guidelines concerning procedures are as follows:

- Review work practices on a regular basis to ensure that they do not differ significantly from formal procedures.
- Review checklist effectiveness in assisting the performance of aircraft maintenance people in routine circumstances such as preparing an aircraft for towing and activating hydraulics.
- Ensure that standard work practices are being followed throughout all maintenance operations.
- Review all documented maintenance procedures and practices on a regular basis with respect to their consistency, accessibility, and realism.

Two useful guidelines pertaining to design are actively seek relevant information on the occurrence of human errors during the maintenance phase to provide appropriate input in the design phase and ensure that all equipment manufacturers give adequate attention to maintenance-related human factors during the design phase. Three guidelines pertaining to human error risk management are as follows:

- Avoid carrying out simultaneously the same maintenance task on similar redundant items.
- Review formally the effectiveness of defences, such as engine runs, built into the system to detect maintenance errors.
- Review the need to disturb normally functioning systems for performing rather nonessential periodic maintenance inspections, because the disturbance may result in a maintenance error.

A useful guideline in the areas of towing aircraft or other equipment is, review the procedures and equipment used for towing to and from all maintenance facilities. Two guidelines in the area of maintenance incident feedback are as follows:

- Ensure that all appropriate personnel in management receive an effective feedback on human factors-related maintenance incidents periodically, with particular consideration to the underlying conditions that promote the occurrence of such incidents.
- Ensure that all personnel involved with training are given an effective feedback on recurring human factors-related maintenance incidents on a regular basis, so that appropriate corrective measures at these problems are targeted effectively.

Two useful guidelines concerning training are periodically provide appropriate training courses to maintenance people with emphasis on company procedures, and consider introducing crew resource management for individuals, directly or indirectly, involved with maintenance. One particular guideline in the area of shift handover is to ensure the adequacy of practices concerned with shift handover by

considering documentation and communication, so that all incomplete tasks are transferred correctly across all shifts.

An important guideline concerning the communication area is to ensure that appropriate systems are in place for disseminating important pieces of information to all concerned with the maintenance activity, so that repeated errors or changing procedures are considered with care.

Finally, a useful guideline pertaining to the supervision area is to recognize that supervision and management oversights need to be strengthened, particularly in the final hours of each shift, as the occurrence of human errors becomes more likely.

## 10.8  Problems

1. Write an essay on human error in aircraft maintenance.
2. List at leas five facts and figures concerned with human error in aircraft maintenance.
3. What are the principal reasons of the occurrence of human error in the maintenance activity?
4. What are the major categories of human errors in aircraft maintenance and inspection tasks?
5. Discuss commonly occurring human errors in aircraft maintenance.
6. Discuss in detail the occurrence of an aircraft accident due to a maintenance error.
7. List at least ten useful guidelines to reduce human error in aircraft maintenance.
8. Prove that the sum of Equations (10.7), (10.9) and (10.10) is equal to $\dfrac{1}{s}$.
9. Obtain steady state probability expressions for Equations (10.11) and (10.15).
10. Prove Equations (10.11), (10.15), and (10.16) by using Equations (10.7), (10.9), and (10.10).

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# 11

# Mathematical Models for Predicting Human Reliability and Error in Transportation Systems

## 11.1 Introduction

Mathematical modeling is a widely used approach in which the components of an item are represented by idealized elements assumed to have all the representative characteristics of real life components, and whose behaviour is possible to be described by equations. However, a mathematical model's degree of realism depends on the assumptions imposed upon it.

Over the years, in the area of reliability engineering, various types of mathematical models have been developed to study human reliability and human error in engineering systems. Many of these models were developed using stochastic processes including the Markov method [1, 2]. Although the effectiveness of such models can vary from one application to another, some of them are being used quite successfully to study various types of real-life problems in the industrial sector [3]. Thus, some of these models can also be useful to study human reliability and error-related problems in transportation systems.

This chapter presents the mathematical models considered useful to perform various types of human reliability and error analysis in transportation systems. Most of these models are based upon the Markov method.

## 11.2 Models for Predicting Human Performance Reliability and Correctability Probability in Transportation Systems

People involved with transportation systems perform various types of time continuous tasks including tracking, operating, and monitoring. In performing such tasks humans can make mistakes or errors and sometime can correct the self-generated

errors as well. Therefore, this section presents two mathematical models to predict human performance reliability and correctability probability.

## 11.2.1  Model I

This model is concerned with predicting the human performance reliability or more specifically, the probability of performing a time continuous task correctly. An expression for predicting human performance reliability is developed as follows [1–5].

The probability of occurrence of human error, say, in a transportation system-related task, in the finite time interval $\Delta t$ with event $Y$ given is

$$P(X/Y)=\gamma(T)\,\Delta T, \tag{11.1}$$

where

$\gamma(t)$   is the human error rate at time t; this is analogous to the hazard rate, $z(t)$, in the classical reliability theory.

$X$     is an event that human error will occur in time interval $[t, t+\Delta t]$.

$Y$     is an errorless performance event of duration $t$.

The joint probability of the errorless performance is expressed by

$$P(\overline{X}/Y)P(Y)=P(Y)-P(X/Y)\,P(Y), \tag{11.2}$$

where

$\overline{X}$    is the event that human error will not occur in time interval $[t, t+\Delta t]$.

$P(Y)$  is the occurrence probability of event $Y$.

It is to be noted that Equation (11.2) denotes an errorless performance probability over time intervals $[0, t]$ and $[t, t+\Delta t]$. Equation (11.2) may be rewritten as follows:

$$R_{\mathrm{h}}(t)-R_{\mathrm{h}}(t)P(X/Y)=R_{\mathrm{h}}(t+\Delta t), \tag{11.3}$$

where

$R_{\mathrm{h}}(t)$  is the human reliability at time $t$.

Substituting Equation (11.1) into Equation (11.3) yields

$$\frac{R_{\mathrm{h}}(t+\Delta t)-R_{\mathrm{h}}(t)}{\Delta t}=-R_{\mathrm{h}}(t)\,\gamma(t). \tag{11.4}$$

In the limiting case Equation (11.4) becomes

$$\lim_{\Delta t \to 0}\frac{R_{\mathrm{h}}(t+\Delta t)-R_{\mathrm{h}}(t)}{\Delta t}=\frac{\mathrm{d}\,R_{\mathrm{h}}(t)}{\mathrm{d}t}=-R_{\mathrm{h}}(t)\,\gamma(t). \tag{11.5}$$

At time $t=0$, $R_{\mathrm{h}}(0)=1$.

By rearranging the two right-hand terms of Equation (11.5), integrating the both sides over the time interval [0, $t$], and using the above initial conditions, we get

$$\int_{1}^{R_{h}(t)} \frac{1}{R_{h}(t)} \cdot dR_{h}(t) = -\int_{0}^{t} \gamma(t) dt.$$
(11.6)

After evaluating the left side of Equation (11.6), we get

$$R_{h}(t) = e^{-\int_{0}^{t} \gamma(t) dt}.$$
(11.7)

The above equation is the general expression to compute human performance reliability for any time to human error statistical distribution (*e.g.*, exponential, gamma, and Weibull).

By integrating Equation (11.7) over the time interval [0, ∞], we obtain the following general expression for the mean time to human error:

$$T_{mhe} = \int_{0}^{\infty} \left[ e^{-\int_{0}^{t} \gamma(t) dt} \right] dt$$
(11.8)

**Example 11.1**
Assume that the error rate of a train driver is 0.0004 errors/hour (*i.e.*, times to human error are exponentially distributed). Calculate the driver's reliability during a 8-hour work period.

Thus, for exponentially distributed times to human error, we have [2]

$$\gamma(t) = 0.0004 \text{ errors/hour.}$$

Substituting the above data and the specified value for time $t$ into Equation (11.7) yields

$$R_{h}(8) = e^{-\int_{0}^{8} (0.0004) dt},$$
$$= e^{-(0.0004)(8)},$$
$$= 0.9968.$$

Thus, the train driver's reliability during the specified work period is 0.9968.

## 11.2.2 Model II

This model is concerned with predicting the probability that a self-generated error will be corrected in time $t$. In Reference [1], the correctability function is defined as the probability that a task error will be corrected in time $t$ subjected to stress constraint associated with the task and its environment. Mathematically, the correctability function may be defined as follows:

$$P_{c}(t) = P(correction \ of \ error \ in \ time \ t \ / \ stress),$$
(11.9)

where

$P$        is the probability.

$P_c(t)$    is the probability that a human error will be corrected in time $t$.

The time derivative of not-correctability function, $\overline{P_c}(t)$, may be defined as follows [1, 2]:

$$\overline{P}'_c(t) = -\frac{1}{N} \cdot N'_{\bar{c}}(t), \tag{11.10}$$

where the prime denotes differentiation with respect to time $t$, and

$N$        is the total number of times task correction is accomplished after time $t$.

$N_{\bar{c}}(t)$    is the total number of times the task is not accomplished after time $t$.

By dividing the both sides of Equation (11.10) by $N_{\bar{c}}(t)$, we get

$$\frac{N.\overline{P}'_c(t)}{N_{\bar{c}}(t)} = -\frac{N'_{\bar{c}}(t)}{N_{\bar{c}}(t)}. \tag{11.11}$$

The right-hand side of Equation (11.11) represents the instantaneous task correction rate $\gamma_c(t)$. Hence, Equation (11.11) may be rewritten to the following form:

$$\frac{\overline{P}'_c(t)}{\overline{P}_c(t)} + \gamma_c(t) = 0. \tag{11.12}$$

By solving Equation (11.12) for given initial conditions, we get

$$\overline{P}_c(t) = e^{-\int_0^t \gamma_c(t)\,dt}. \tag{11.13}$$

Since $P_c(t) + \overline{P}_c(t) = 1$, we write

$$P_c(t) = 1 - \overline{P}_c(t),$$
$$= 1 - e^{-\int_0^t \gamma_c(t)\,dt}. \tag{11.14}$$

It is to be noted that Equation (11.14) is a general expression that holds for both constant and non-constant task correction rates. More specifically, it holds whether the tasks correction rate is described by the exponential distribution or any other statistical distribution such as Rayleigh.

**Example 11.2**

Assume that a train driver's self-generated error correction times are Rayleigh distributed. Thus, his/her task correction rate is expressed by

$$\gamma_c(t) = \frac{2\,t}{\mu^2}, \tag{11.15}$$

where
$\mu$ is the distribution scale parameter.

Obtain an expression for train driver's correctability function (*i.e.*, $P_c(t)$).
By substituting Equation (11.15) into Equation (11.14) we obtain

$$P_c(t) = 1 - e^{-\int_0^t \frac{2t}{\mu^2} \, dt},$$

$$= 1 - e^{-\frac{t^2}{\mu^2}}. \tag{11.16}$$

Thus, Equation (11.16) is the expression for train driver's correctability function.

# 11.3 Models for Predicting Human Performance Reliability Subject to Critical and Noncritical Human Errors, and Fluctuating Environment in Transportation Systems

Over the years various types of mathematical models have been developed to perform human performance reliability analysis subject to fluctuating environment, critical and noncritical human errors, *etc.* This section presents two such models developed by using the Markov method, for application in the area of transportation systems.

## 11.3.1 Model I

This model represents an operator in transportation systems (*e.g.*, driver, pilot, *etc.*) performing a time continuous task subjected to critical and noncritical errors. More specifically, the errors committed by the operator are divided into two groups: critical and noncritical. The model can be quite useful to obtain information such as follows:

- The operator performance reliability at time $t$.
- The operator mean time to error.
- The probability of the operator committing a critical error at time $t$.
- The probability of the operator committing a noncritical error at time $t$.

The model state space diagram is shown in Figure 11.1 and the numerals in the diagram circles denote the states of the transportation system operator. The following assumptions are associated with the model:

- Human errors occur independently.
- Both critical and noncritical human error rates are constant.
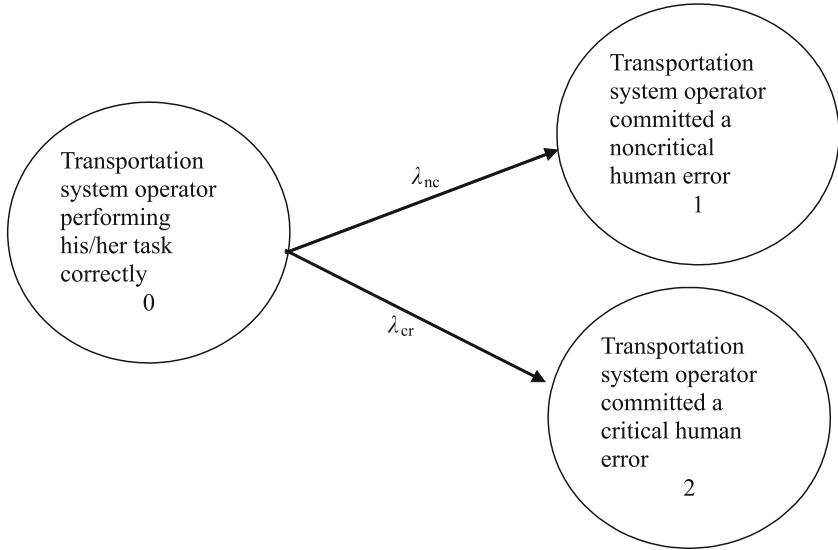
**Figure 11.1.** State space diagram for the transportation system operator subjected to critical and noncritical human errors

The following symbols are associated with the model:

$\lambda_{nc}$   is the constant noncritical human error rate of the transportation system operator.

$\lambda_{cr}$   is the constant critical human error rate of the transportation system operator.

$j$   is the $j$th state of transportation system operator; $j=0$ means that the transportation system operator performing his/her task correctly, $j=1$ means that the transportation system operator has committed a noncritical human error, $j=2$ means that the transportation system operator has committed a critical human error.

$P_j(t)$   is the probability of the transportation system operator in state $j$ at time t, for $j=0, 1, 2$.

By using the Markov method, we write down the following set of equations for the Figure 11.1 diagram [6, 7]:

$$\frac{dP_0(t)}{dt} + (\lambda_{nc} + \lambda_{cr}) P_0(t) = 0, \tag{11.17}$$

$$\frac{dP_1(t)}{dt} - \lambda_{nc} P_0(t) = 0, \tag{11.18}$$

$$\frac{dP_2(t)}{dt} - \lambda_{cr} P_0(t) = 0. \tag{11.19}$$

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

By solving Equations (11.17)–(11.19), we get

$$P_0(t) = e^{-(\lambda_{nc} + \lambda_{cr})t},$$

(11.20)

$$P_1(t) = \frac{\lambda_{nc}}{\lambda_{nc} + \lambda_{cr}} \left[ 1 - e^{-(\lambda_{nc} + \lambda_{cr})t} \right],$$

(11.21)

$$P_2(t) = \frac{\lambda_{cr}}{\lambda_{cr} + \lambda_{nc}} \left[ 1 - e^{-(\lambda_{nc} + \lambda_{cr})t} \right].$$

(11.22)

The above three equations can be used to obtain transportation system operator's probabilities being in state 0, 1, and 2. The transportation system operator's performance reliability is given by

$$R_{tp} = P_0(t),$$
$$= e^{-(\lambda_{nc} + \lambda_{cr})t}.$$

(11.23)

where
$R_{tp}(t)$ is the transportation system operator's performance reliability.

The transportation system operator's mean time to human error is given by [2, 7]

$$MTTHE_{tp} = \int_0^\infty R_{tp}(t)\, dt,$$

$$= \int_0^\infty e^{-(\lambda_{nc} + \lambda_{cr})t}\, dt,$$

(11.24)

$$= \frac{1}{\lambda_{nc} + \lambda_{cr}}.$$

where
$MTTHE_{tp}$ is the transportation system operator's mean time to human error.

**Example 11.3**
A transportation system operator's constant critical and noncritical human error rates are 0.0025 errors/hour and 0.0005 errors/hour, respectively. Calculate the transportation system operator's reliability for a 8-hour mission and mean time to human error.
By substituting the specified data values into Equations (11.23) and (11.24), we get

$$R_{tp}(8) = e^{-(0.0005 + 0.0025)\,8},$$
$$= 0.9763.$$

and

$$MTTHE_{tp} = \frac{1}{0.0005 + 0.0025},$$
$$= 333.3 \text{ hours.}$$

Thus, the transportation system operator's reliability and mean time to human error are 0.9763 and 333.3 hours, respectively.

## 11.3.2  Model II

This model represents a transportation system operator (*e.g.*, driver, pilot, *etc.*) performing time continuous task under fluctuating environment (*i.e.*, normal and stressful) [2, 8]. An example of such environment is weather changing from normal to stormy and vice-versa. As the rate of operator errors from normal environment to stressful environment can vary quite significantly, this model can be used to calculate the transportation system operator's performance reliability and mean time to human error under the fluctuating environment. More specifically, the model considers two separate operator error rates (*i.e.*, in normal and stormy environments).

The state space diagram of the model is shown in Figure 11.2 and the numerals in the diagram boxes and circles denote the transportation system operator's states.

The model is subjected to the following three assumptions:

- All operator errors occur independently.
- Operator error rates are constant.
- Rates of the environment changing from normal to stressful and vice versa are constant.
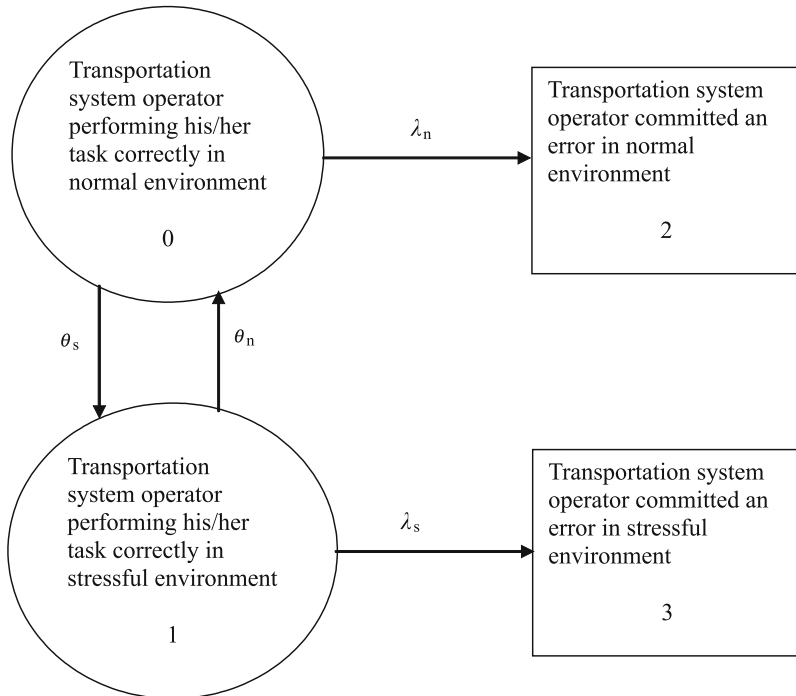


**Figure 11.2.** State space diagram for the transportation system operator performing his/her time continuous task in fluctuating normal and stressful environments

The following symbols are associated with the model:

$\lambda_n$    is the constant error rate of the transportation system operator working in normal environment.

$\lambda_s$    is the constant error rate of the transportation system operator working in stressful environment.

$\theta_n$    is the constant transition rate from stressful environment to normal environment.

$\theta_s$    is the constant transition rate from normal environment to stressful environment.

$j$    is the jth state of the transportation system operator; $j = 0$ means that the transportation system operator performing his/her task correctly in normal environment, $j = 1$ means that the transportation system operator performing his/her task correctly in stressful environment, $j = 2$ means that the transportation system operator has committed an error in normal environment, $j = 3$ means that the transportation system operator has committed an error in stressful environment.

$P_j(t)$ is the probability of the transportation system operator being in state $j$ at time $t$, for $j = 0, 1, 2, 3$.

By using the Markov method, we write down the following equations for the Figure 11.2 diagram [8]:

$$\frac{dP_0(t)}{dt} + \left(\lambda_n + \theta_s\right) P_0(t) = \theta_n\, P_1(t), \tag{11.25}$$

$$\frac{dP_1(t)}{dt} + \left(\lambda_s + \theta_n\right) P_1(t) = \theta_s\, P_0(t), \tag{11.26}$$

$$\frac{dP_2(t)}{dt} = \lambda_n\, P_0(t), \tag{11.27}$$

$$\frac{dP_3(t)}{dt} = \lambda_s\, P_1(t). \tag{11.28}$$

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

Solving Equations (11.25)–(11.28) by using Laplace transforms yield the following state probability equations:

$$P_0(t) = \frac{1}{\left(x_2 - x_1\right)} \left[\left(x_2 + \lambda_s + \theta_n\right) e^{x_2 t} - \left(x_1 + \lambda_s + \theta_n\right) e^{x_1 t}\right], \tag{11.29}$$

where

$$x_1 = \left[-b_1 + \left(b_1^2 - 4b_2\right)^{1/2}\right] \Big/ 2, \tag{11.30}$$

$$x_2 = \left[-b_1 - \left(b_1^2 - 4b_2\right)^{1/2}\right] \Big/ 2, \tag{11.31}$$

$$b_1 = \lambda_n + \lambda_s + \theta_n + \theta_s, \tag{11.32}$$

$$b_2 = \lambda_n \left( \lambda_s + \theta_n \right) + \theta_s \, \lambda_s, \tag{11.33}$$

$$P_2 \left( t \right) = b_4 + b_5 \, e^{x_2 \, t} - b_6 \, e^{x_1 \, t}, \tag{11.34}$$

where

$$b_3 = \frac{1}{x_2 - x_1}, \tag{11.35}$$

$$b_4 = \lambda_n \left( \lambda_s + \theta_n \right) / x_1 \, x_2, \tag{11.36}$$

$$b_5 = b_3 \left( \lambda_n + b_4 \, x_1 \right), \tag{11.37}$$

$$b_6 = b_3 \left( \lambda_n + b_4 \, x_2 \right), \tag{11.38}$$

$$P_1 \left( t \right) = \theta_s \, b_3 \left( e^{x_2 \, t} - e^{x_1 \, t} \right), \tag{11.39}$$

$$P_3 \left( t \right) = b_7 \left[ \left( 1 + b_3 \right) \left( x_1 \, e^{x_2 \, t} - x_2 \, e^{x_1 \, t} \right) \right] \tag{11.40}$$

where

$$b_7 = \lambda_s \, \theta_s / x_1 \, x_2. \tag{11.41}$$

The performance reliability of the transportation system operator is expressed by

$$R_{pso} \left( t \right) = P_0 \left( t \right) + P_1 \left( t \right), \tag{11.42}$$

where
$R_{pso}(t)$ is the transportation system operator reliability at time $t$.

The transportation system operator's mean time to human error is given by [2, 7]

$$MTTHE_{pso} = \int_0^{\infty} R_{pso} \left( t \right) dt, \tag{11.43}$$

$$= \left( \lambda_s + \theta_s + \theta_n \right) / b_2, \tag{11.44}$$

where
$MTTHE_{pso}$ is the transportation system operator's mean time to human error.


**Example 11.4**
A transportation system operator's constant error rates in normal and stressful environments are 0.0004 errors/hour and 0.0006 errors/hour, respectively. The constant transition rates from normal to stressful environment and vice-versa are 0.04 times per hour and 0.02 times per hour, respectively. Calculate the transportation system operator's mean time to human error.

By substituting the specified data values into Equation (11.44), we get

$$MTTHE_{pso} = \frac{0.0006 + 0.04 + 0.02}{0.0004(0.0006 + 0.02) + (0.0006)(0.04)},$$

$$= 1879.6 \text{ hours.}$$

Thus, the transportation system operator's mean time to human error is 1879.6 hours.

# 11.4  Models for Performing Human Error Analysis in Transportation Systems

Over the years many mathematical models have been developed to perform various types of human error analysis in transportation systems [9–10]. This section presents three such models.

## 11.4.1  Model I

This model represents an on-surface transit system subjected to two types of failures: hardware failures and failures due to human errors [2, 9]. An example of such system is an operating vehicle that can fail either due to hardware failure or a failure
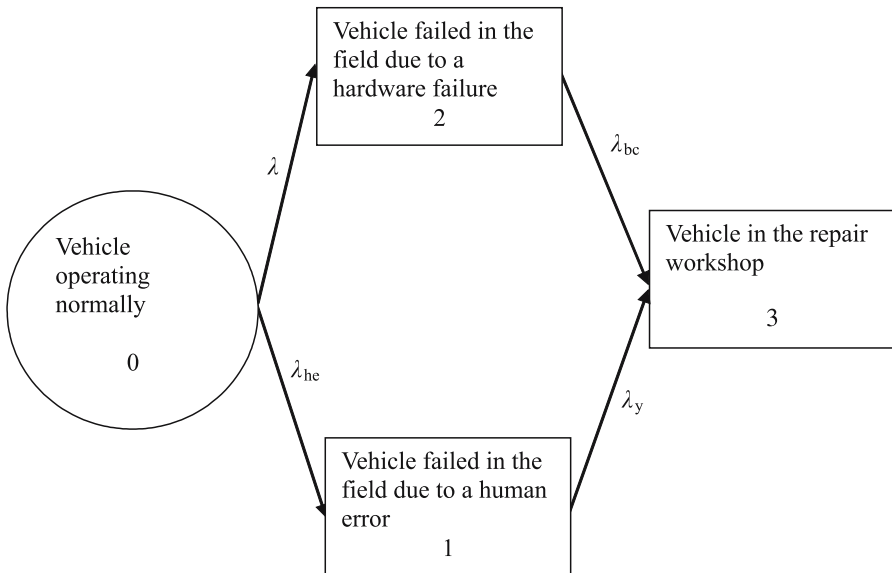


**Figure 11.3.** State space diagram for a vehicle failing due to a hardware failure or a human error

caused by a human error. The failed vehicle is towed to the repair workshop. The state space diagram of the model is shown in Figure 11.3. The numerals in the diagram circle and boxes denote system states. The following assumptions are associated with the model:

- Failures and human errors occur independently.
- All failure rates are constant.
- The towing rates are constant.
- The vehicle can fail completely either due to hardware failures or due to human errors.

The following symbols are associated with the model:

$i$      is the $i$th state of the on-surface transit system (*i.e.*, vehicle); $i=0$ means that the vehicle operating normally, $i=1$ means that the vehicle has failed in the field due to a human error, $i=2$ means that the vehicle has failed in the field due to a hardware failure, $i=3$ means that the vehicle is in the repair workshop.

$P_j(t)$ is the probability that the on-surface transit system (*i.e.*, vehicle) is in state $i$ at time $t$, for $i=0, 1, 2, 3$.

$\lambda$      is the vehicle constant hardware failure rate.

$\lambda_{he}$    is the vehicle constant failure rate due to human errors.

$\lambda_x$     is the vehicle constant towing rate from system state 2 to state 3.

$\lambda_y$     is the vehicle constant towing rate from system state 1 to state 3.

With the aid of the Markov method, we write down the following equations for the Figure 11.3 diagram [2, 9 , 10]:

$$\frac{\mathrm{d}P_0(t)}{\mathrm{d}t} + (\lambda + \lambda_{he})P_0(t) = 0, \tag{11.45}$$

$$\frac{\mathrm{d}P_1(t)}{\mathrm{d}t} + \lambda_y\,P_1(t) = \lambda_{he}\,P_0(t), \tag{11.46}$$

$$\frac{\mathrm{d}P_2(t)}{\mathrm{d}t} + \lambda_x\,P_2(t) = \lambda\,P_0(t), \tag{11.47}$$

$$\frac{\mathrm{d}P_3(t)}{\mathrm{d}t} = \lambda_x\,P_2(t) + \lambda_y\,P_1(t). \tag{11.48}$$

At time $t=0$, $P_0(0)=1$, and $P_1(0)=P_2(0)=P_3(0)=0$.
Solving Equations (11.45)–(11.48) by using Laplace transforms, we get

$$P_0(t) = \mathrm{e}^{-ct}, \tag{11.49}$$

where

$$c = \lambda + \lambda_{he} \tag{11.50}$$

$$P_1(t) = c_1 \left( e^{-ct} - e^{-\lambda_y t} \right), \tag{11.51}$$

where

$$c_1 = \lambda_{he} \big/ \left( \lambda_y - c \right), \tag{11.52}$$

$$P_2(t) = c_2 \left( e^{-ct} - e^{-\lambda_x t} \right), \tag{11.53}$$

where

$$c_2 = \lambda \big/ \left( \lambda_x - c \right), \tag{11.54}$$

$$P_3(t) = 1 + c_1 e^{-\lambda_y t} + c_2 e^{-\lambda_x t} + c_3 e^{-ct}, \tag{11.55}$$

where

$$c_3 = -\left( c_1 \lambda_y + c_2 \lambda_x \right) \big/ c. \tag{11.56}$$

The vehicle or transit system reliability is given by

$$R_v(t) = P_0(t) = e^{-ct}, \tag{11.57}$$

where
$R_v(t)$ is the vehicle or transit system reliability at time $t$.

The vehicle mean time to failure is given by [7]

$$MTTF_v = \int_0^\infty R_v(t)\, dt,$$

$$= \int_0^\infty e^{-ct}\, dt, \tag{11.58}$$

$$= \frac{1}{c} = \frac{1}{\lambda + \lambda_{he}},$$

where
$MTTF_v$ is the vehicle mean time to failure.

## Example 11.5
Assume that constant hardware failure and failure due to human error, rates of a vehicle are 0.0008 failures/hour and 0.0001 failures/hour, respectively. Calculate the vehicle reliability for an 10-hour mission and mean time to failure.
Substituting the specified data values into Equation (11.57) yields

$$R_v(10) = e^{-(0.0008+0.0001)\,(10)},$$
$$= 0.9910.$$

Similarly, by inserting the given data values into Equation (11.58), we get

$$MTTF_\upsilon = \frac{1}{0.0008 + 0.0001},$$
$$= 1111.1 \text{ hours.}$$

Thus, the vehicle reliability and mean time to failure are 0.9910 and 1111.1 hours, respectively.

## 11.4.2  Model II

This model is basically same as the previous model (*i.e.*, Model I) but with one exception, *i.e.*, the failed vehicle is repaired. More specifically, when the vehicle fails in the field, repair is attempted. If it cannot be repaired, then the vehicle is towed to the repair facility for repair. The redrawn diagram of Figure 11.3 is shown in Figure 11.4 with constant repair rates. Thus, Figure 11.4 is the state space diagram for this model. The assumptions associated with this model are the same as for Model I. The symbols used to denote vehicle repair rates are defined below.

$\mu_\upsilon$   is the constant repair rate of the vehicle from the repair workshop (*i.e.*, state 3).

$\mu$    is the constant repair rate of the vehicle when failed in the field due to a hardware failure.

$\mu_{he}$  is the constant repair rate of the vehicle when failed in the field due a human error.

Other symbols used in this model are the same as for Model I. By using the Markov method, we write down the following Equations for the Figure 11.4 diagram [2, 9]:
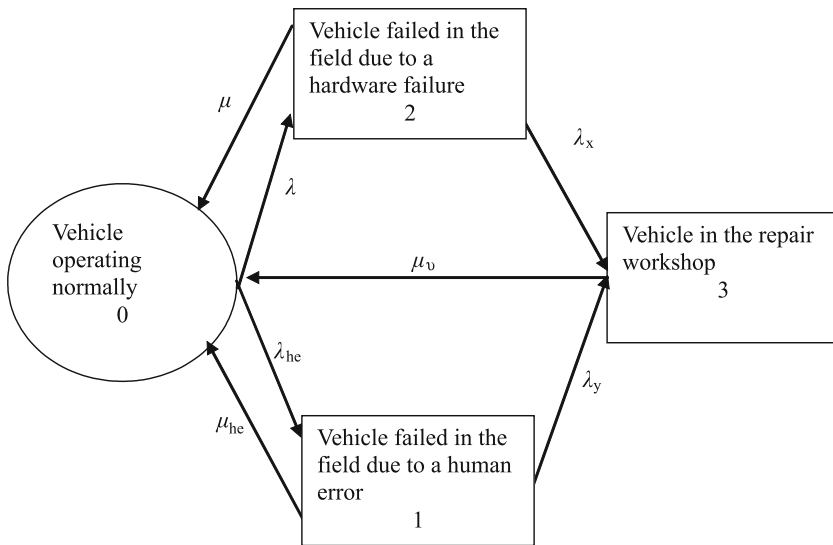


**Figure 11.4.** Redrawn Figure 11.3 diagram with constant repair rates

$$\frac{dP_0(t)}{dt} + (\lambda + \lambda_{he}) P_0(t) = \mu_{he} P_1(t) + \mu P_2(t) + \mu_v P_3(t), \qquad (11.59)$$

$$\frac{dP_1(t)}{dt} + (\lambda_y + \mu_{he}) P_1(t) = \lambda_{he} P_0(t), \qquad (11.60)$$

$$\frac{dP_2(t)}{dt} + (\lambda_x + \mu) P_2(t) = \lambda P_0(t), \qquad (11.61)$$

$$\frac{dP_3(t)}{dt} + \mu_v P_3(t) = \lambda_y P_1(t) + \lambda_x P_2(t). \qquad (11.62)$$

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

By setting the derivatives equal to zero in Equations (11.59)–(11.62) and using the relationship $\sum_{i=0}^{3} P_i = 1$, we get the following steady state probability equations [7]:

$$P_0 = \frac{A}{B}, \qquad (11.63)$$

and

$$P_i = m_i P_0, \qquad \text{for } i = 1, 2, 3 \qquad (11.64)$$

where

$$A = \mu_v (\lambda_y + \mu_{he})(\lambda_x + \mu), \qquad (11.65)$$

$$B = (\lambda_y + \mu_{he})\left[\mu_v (\lambda_x + \mu) + \lambda (\mu_v + \lambda_x)\right] + \lambda_{he} (\lambda_x + \mu)(\lambda_y + \mu_v), \quad (11.66)$$

$$m_1 = \lambda_{he}/(\lambda_y + \mu_{he}), \qquad (11.67)$$

$$m_2 = \lambda/(\lambda_x + \mu), \qquad (11.68)$$

$$m_3 = \frac{\lambda_{he} \lambda_y (\lambda_x + \mu) + \lambda \lambda_x (\lambda_y + \mu_{he})}{\mu_v (\lambda_y + \mu_{he}) (\lambda_x + \mu)}. \qquad (11.69)$$

$P_i$ is the steady state probability of the vehicle being in state $i$, for $i = 0, 1, 2, 3$.

The steady state availability and unavailability of the vehicle are given by

$$A_{vss} = P_0, \qquad (11.70)$$

and

$$UA_{vss} = P_1 + P_2 + P_3, \qquad (11.71)$$

where

$A_{vss}$ is the vehicle steady state availability.

$UA_{vss}$ is the vehicle steady state unavailability.

### 11.4.3  Model III

This model represents an on-surface transit system (*e.g.*, a vehicle) that can either fail safely or fail with accident due to human errors or hardware failures [2, 10]. The failed system is taken to the repair shop. After repair, it is put back into normal operation. The model state space diagram is shown in Figure 11.5 and the numerals in diagram circles and box denote system states. The model is subjected to the following assumptions:

- All failures and errors are statistically independent.
- Failure, human error, towing, and repair rates are constant.
- The repaired system is as good as new.
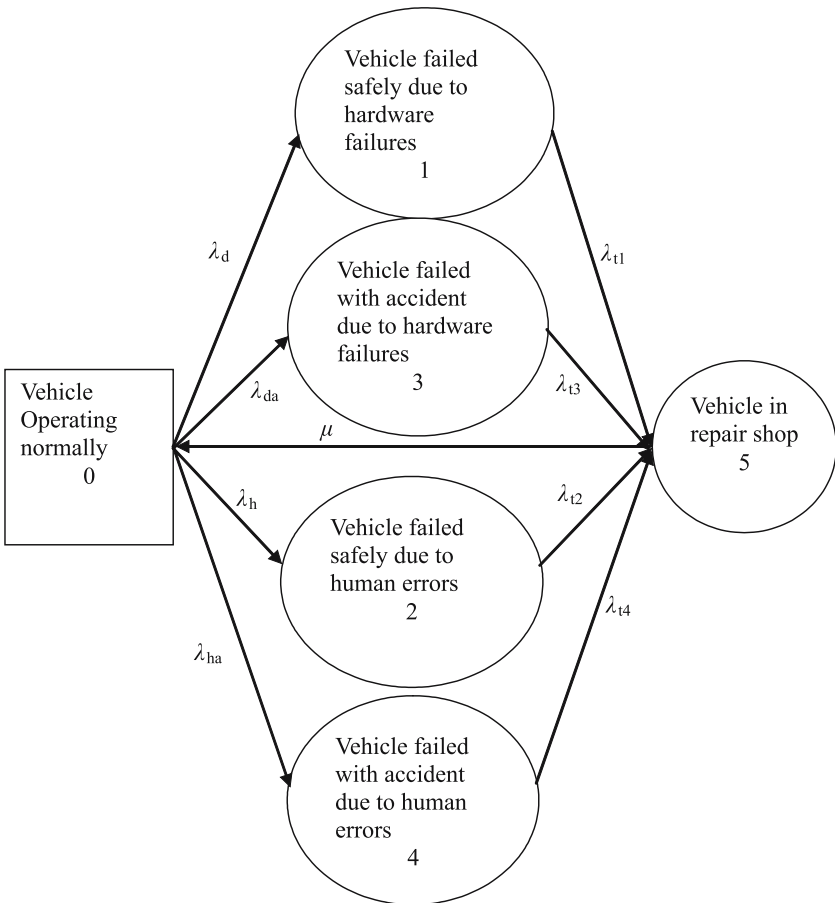


**Figure 11.5.** State space diagram for a vehicle that can either fail safely or fail with accident due to hardware failures or human errors

The following symbols are associated with the model:

$i$     is the ith state of the on-surface system (*i.e.*, vehicle);

$i=0$   means that the vehicle operating normally,

$i=1$   means that the vehicle has failed safely due to hardware failures,

$i=2$   means that the vehicle has failed safely due to human errors,

$i=3$   means that the vehicle has failed with accident due to hardware failures,

$i=4$   means that the vehicle has failed with accident due to human errors,

$i=5$   means that the vehicle is in repair shop.

$P_j(t)$   is the probability that the on-surface transit system (*i.e.*, vehicle) is in state $i$ at time $t$, for $i=0, 1, 2, 3, 4, 5$.

$\lambda_d$    is the constant hardware failure rate of the vehicle failing safely.

$\lambda_h$    is the constant vehicle safe-failure human error rate.

$\lambda_{da}$   is the constant hardware failure rate of the vehicle that cause an accident.

$\lambda_{ha}$   is the constant human error rate of the vehicle that cause an accident.

$\lambda_{ti}$    is the constant vehicle towing rate from state $i$ to state 5, for $i=1, 2, 3, 4$.

$\mu$     is the constant vehicle repair rate form state 5 to state 0.

$P_i$    is the steady state probability that the on-surface transit system (*i.e.*, vehicle) is in state $i$, for $i=0, 1, 2, 3, 4, 5$.

With the aid of the Markov method, we write down the following equations for the Figure 11.5 diagram [2, 7, 10]:

$$\frac{dP_0(t)}{dt} + \left(\lambda_d + \lambda_{da} + \lambda_h + \lambda_{ha}\right) P_0(t) = \mu P_5(t), \tag{11.72}$$

$$\frac{dP_1(t)}{dt} + \lambda_{t1} P_1(t) = \lambda_d P_0(t), \tag{11.73}$$

$$\frac{dP_2(t)}{dt} + \lambda_{t2} P_2(t) = \lambda_h P_0(t), \tag{11.74}$$

$$\frac{dP_3(t)}{dt} + \lambda_{t3} P_3(t) = \lambda_{da} P_0(t), \tag{11.75}$$

$$\frac{dP_4(t)}{dt} + \lambda_{t4} P_4(t) = \lambda_{ha} P_0(t), \tag{11.76}$$

$$\frac{dP_5(t)}{dt} + \mu P_5(t) = \lambda_{t1} P_1(t) + \lambda_{t2} P_2(t) + \lambda_{t3} P_3(t) + \lambda_{t4} P_4(t). \tag{11.77}$$

At time $t=0$, $P_0(0)=1$, and $P_1(0)=P_2(0)=P_3(0)=P_4(0)=P_5(0)=0$.
By setting $\mu=0$ in Equations (11.72)–(11.77) and then solving for $P_0(t)$, we get

$$R_{vs}(t) = P_0(t) = e^{-(\lambda_d + \lambda_{da} + \lambda_h + \lambda_{ha})t}, \tag{11.78}$$

where
$R_{v_s}(t)$ is the vehicle reliability at time $t$.

The vehicle mean time to failure is given by [7]

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

$$= \int_0^\infty e^{-(\lambda_d + \lambda_{da} + \lambda_h + \lambda_{ha})\,t}\,dt, \tag{11.79}$$

$$= \frac{1}{\lambda_d + \lambda_{da} + \lambda_h + \lambda_{ha}}.$$

By setting derivatives equal to zero in Equations (11.72)–(11.77) and using the relationship $\sum_{i=0}^{5} P_i = 1$, we obtain the following steady state probability equations [7]:

$$P_0 = \frac{1}{1 + D_1}, \tag{11.80}$$

and

$$D_1 = \frac{\lambda_d}{\lambda_{t1}} + \frac{\lambda_h}{\lambda_{t2}} + \frac{\lambda_{da}}{\lambda_{t3}} + \frac{\lambda_{ha}}{\lambda_{t4}} + \frac{D_2}{\mu}, \tag{11.81}$$

$$D_2 = \lambda_d + \lambda_{da} + \lambda_h + \lambda_{ha}, \tag{11.82}$$

$$P_1 = \frac{\lambda_d}{\lambda_{t1}} \cdot P_0, \tag{11.83}$$

$$P_2 = \frac{\lambda_h}{\lambda_{t2}} \cdot P_0, \tag{11.84}$$

$$P_3 = \frac{\lambda_{da}}{\lambda_{t3}} \cdot P_0, \tag{11.85}$$

$$P_4 = \frac{\lambda_{ha}}{\lambda_{t4}} \cdot P_0, \tag{11.86}$$

$$P_5 = \frac{D_2}{\mu} \cdot P_0. \tag{11.87}$$

The vehicle steady state availability and unavailability are given by

$$AV_{ss} = P_0, \tag{11.88}$$

and

$$UAV_{ss} = P_1 + P_2 + P_3 + P_4 + P_5, \tag{11.89}$$

where
$AV_{ss}$    is the vehicle steady state availability.
$UAV_{ss}$  is the vehicle steady state unavailability.

The steady state probability of the vehicle failing safely is expressed by

$$P_{sss} = P_1 + P_2. \tag{11.90}$$

Similarly, the steady state probability of the vehicle failing with an accident is

$$P_{ssa} = P_3 + P_4. \tag{11.91}$$

The steady state probability of the vehicle failing due to human error is

$$P_{sshe} = P_2 + P_4. \tag{11.92}$$

Finally, the steady state probability of the vehicle failing due to hardware failures is given by

$$P_{sshf} = P_1 + P_3. \tag{11.93}$$

**Example 11.6**
Assume that in Figure 11.5, we have the following specified values for some transition rates:

$\lambda_d = 0.0006$ failures / hour
$\lambda_{da} = 0.0002$ failures / hour
$\lambda_h = 0.0003$ errors / hour
$\lambda_{ha} = 0.0001$ errors / hour

Calculate the vehicle reliability for an 8-hour mission and mean time to failure. Inserting the given data into Equation (11.78) yields

$$R_{vs}(8) = e^{-(0.0006+0.0002+0.0003+0.0001)(8)},$$
$$= 0.9904.$$

Similarly, by inserting the specified data values into Equation (11.79), we get

$$MTTF_{vs} = \frac{1}{(0.0006+0.0002+0.0003+0.0001)},$$
$$= 833.3 \text{ hours.}$$

Thus, the vehicle reliability and mean time to failure are 0.9904 and 833.3 hours, respectively.

## 11.5  Problems

1. Write an essay on mathematical models used for performing human reliability and error analysis in transportation systems.
2. Assume that in Equation (11.7), the human error rate, $\gamma(t)$, at time $t$ follows the Weibull distribution. Obtain an expression for the human reliability, $R_{\mathrm{h}}(t)$.
3. Prove Equation (11.14) by using Equation (11.12).
4. Compare human performance reliability and correctability functions.
5. Assume that the constant error rate of a truck driver is 0.0006 errors/hour. Calculate the driver's reliability during a 10-hour work period.
6. Prove Equations (11.20)–(11.22).
7. Prove that the sum of Equations (11.49), (11.51), (11.53), and (11.55) is equal to unity.
8. Prove Equations (11.63) and (11.64).
9. Solve Equations (11.72)–(11.77).
10. Assume that a vehicle operator's constant error rates in normal and stressful environments are 0.0007 errors/hour and 0.0009 errors/hour, respectively. The constant transition rates from normal to stressful environment and vice versa are 0.06 times per hour and 0.03 times per hour, respectively. Calculate the vehicle operator's mean time to human error.

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# Appendix

# Bibliography: Literature on Human Reliability and Error in Transportation Systems

## A.1 Introduction

Over the years, many publications on human reliability and error in transportation systems have appeared in the form of journal articles, conference proceedings articles, technical reports, *etc.* This appendix presents an extensive list of publications, directly or indirectly, related to human reliability and error in transportation systems.

The period covered by the listing is 1968–2006. The main objective of this listing is to provide readers with sources for obtaining additional information on human reliability and error in transportation systems.

## A.2 Publications

1    Ahlstrom, U., Work Domain Analysis for Air Controller Weather Displays, Journal of Safety Research, Vol. 36, 2005, pp.159–169.
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# Author Biography

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 Mechanical Engineering Department/Engineering Management Program for over ten years at the same institution. He has published over 330 articles on engineering management, reliability, safety, *etc.* He is or has been on the editorial boards of nine international scientific journals. In addition, Dr. Dhillon has written 31 books on various aspects of 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 70 countries, and many of them are translated into languages such as German, Russian and Chinese. He has served as General Chairman of two international conferences on reliability and quality control held in Los Angeles and Paris in 1987.

Prof. Dhillon has 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 27 years, and he has also lectured in over 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 Conf./Workshop on Surgical Errors (sponsored by White House Health and Safety Committee and Pentagon), held at the Capitol Hill (One Constitution Avenue, Washington, D.C.).

Professor Dhillon attended the University of Wales, where he received a B.S. in electrical and electronic engineering and an M.S. in mechanical engineering. He received a Ph.D. in industrial engineering from the University of Windsor.

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