

Contents

Foreword..... xvii

Acknowledgments..... xix

Introduction..... xxi

Section 1: Theory

Chapter 01 - Relevant Data/Statistics

1.1. Introduction3

1.2. Global Relevance of Car Fires4

1.2.1. Safety Concerns4

1.2.2. Road Transportation Disruptions.....4

1.2.3. Impact on Airport Operations4

1.2.4. Maritime Transport Risks4

1.2.5. Insurance Market Influence.....4

1.2.6. Environmental Consequences4

1.2.7. Manufacturing and Design Implications ...4

1.2.8. Technological Advancements and
Safety Standards.....5

1.3. Global Vehicle Fire Data.....5

1.3.1. US5

1.3.2. UK.....5

1.3.3. Other International Data.....5

1.4. Car Fires in Ships and Large Parking
Structures.....6

1.4.1. Transportation Vessels.....6

1.4.1.1. Sincerity Ace (December 2018). .7

1.4.1.2. Felicity Ace (February 2022)7

1.4.1.3. Fremantle Highway
(July 2023)7

1.4.2. Car Fires in Large Parking Structures. .8

1.4.2.1. Liverpool Echo Arena
(December 2017)8

1.4.2.2. Norway Stavanger (Sola)
Airport (January 2020).....9

1.4.2.3. London Luton Airport
(October 2023)9

1.5. Area of Origin, Cause, and Item First
Ignited9

1.6. Car Fire Rates by Type11

1.7. Recalls Related to Fire Risk11

1.8. xEV Situation when Fire Started11

References12

Chapter 02 - Automotive Fire Science
Fundamentals

2.1. Introduction15

2.2. Fire Triangle15

2.3. Fire Tetrahedron.....16

2.3.1. Chain Reaction16

2.3.2. Free Radicals.....17

2.4. Combustible Materials/Fuels17

2.5. Oxidizer18

2.6. Energy Source18

2.7. Explosion19

2.8. Airbags19

2.9. Flash Point20

2.10. Fire Point20

2.11. Autoignition Temperature21

2.12. Flammability Classifications.....21

2.13. Flammability Range22

2.14. Heat Transfer: Conduction, Convection,
and Radiation22

2.14.1. Conduction22

2.14.2. Convection.....22

2.14.3. Radiation23

2.15. Pyrolysis and Carbonization.....23

2.15.1. Pyrolysis.....23

2.15.2. Carbonization24

2.16. Fluid Leakages24

2.17. Hot Surfaces	25
2.18. Electric Anomalies	25
2.19. Fire Accelerants	25
2.20. Heat Release Rate	25
2.21. Fire Extinction Methods	26
2.21.1. Water-Based Methods	27
2.21.2. Foam-Based Methods	27
2.21.3. Dry Powder	27
2.21.4. Inert Gases	27
2.21.5. Chain Reaction Interruption	27
2.21.6. Fire Blankets	27
2.21.7. xEV Fire Extinction	28
References	28

Chapter 03 - Mechanical Sources of Heat, Stress, and Degradation

3.1. Introduction	31
3.2. Vibration	31
3.2.1. Sources of Vibration	32
3.2.1.1. Engine	32
3.2.1.2. Drivetrain	32
3.2.1.3. Imbalanced Rotating Components	32
3.2.1.4. Road Conditions	32
3.2.2. Damaging Effects	32
3.2.2.1. Cracks, Fractures, and Fatigue Failure	32
3.2.2.2. Wear and Tear	33
3.2.2.3. Fasteners and Bolts	34
3.2.2.4. Electronics and Wiring	34
3.3. Impacts	34
3.4. Pressure	35
3.4.1. Fuel System	35
3.4.2. Hydraulic and Lubrication Systems	35
3.5. Cuts	35
3.6. Crushing	35
3.7. Stretching	35
3.8. Friction	36
3.9. Rodents	36

3.10. Mechanical Overloads	37
3.11. Degradation of Pipelines, Seals, and Hydraulic Connections	38
References	39

Chapter 04 - Electric Sources of Heat and Degradation

4.1. Introduction	41
4.2. Intended/Intrinsic Heat Generators	42
4.3. Electric Overload/Series Resistance Increase	42
4.3.1. Electric Overload	43
4.3.2. Series Resistance Increase	43
4.4. Electric Leakages/Parallel Resistance Decrease	43
4.5. Harness Degradations	44
4.5.1. Series Resistance Increase	44
4.5.2. Cable Rupture	45
4.5.3. Short Circuits	45
4.5.4. Copper Beads	45
4.5.5. Water Intrusion	46
4.5.6. Leakage Current	47
4.6. Connection Degradations	47
4.6.1. Loose Ground Connection	48
4.6.2. Incomplete Connector Mating	48
4.6.3. Deformed and Broken Contacts	48
4.6.4. Pushed Back Pins	49
4.6.5. Bad Crimp	49
4.6.6. Oxidation and Corrosion	49
4.6.7. Fretting Corrosion	50
4.6.8. Leakage Currents	51
4.6.9. Damaged Housing	51
4.7. Electric Transients and EMI	51
4.8. Fuse × Wire Gage	53
4.9. Short Circuits	53
4.10. High-Voltage Arcing	54
4.11. Lightning	54
4.12. Improper Accessory Installation	55
References	55

Chapter 05 - Other Degradation Mechanisms

5.1. Introduction	57
5.2. Ultraviolet (UV) Radiation	57
5.2.1. Plastics	58
5.2.2. Rubber	58
5.3. Infrared Radiation (IR)	58
5.4. Sunlight	58
5.5. Thermal Damage	59
5.5.1. Extremely Cold Temperatures	59
5.5.2. Extremely Hot Temperatures	59
5.5.3. Cooling System Failures	59
5.5.4. Plastic Deformation of Polymers	59
5.5.5. Expansion/Contraction Stresses	60
5.5.6. Thermal Cycles Leading to Fatigue	60
5.6. Exhaust System Failures	60
5.7. Water	61
5.7.1. Humidity	61
5.7.2. Condensation	61
5.7.3. Drizzle and Rain	61
5.7.4. Snow and Ice	62
5.7.5. Washing	63
5.7.6. Pools in Potholes and Flooding	63
5.7.7. Sea Water	64
5.8. Aggressive Chemicals	64
5.8.1. Engine Coolant	64
5.8.2. Brake Fluid	64
5.8.3. Fuel	65
5.8.4. Acids	65
5.8.5. Salt and De-Icing Chemicals	65
5.8.6. Other Substances	65
5.9. Solid Particles	66
5.9.1. Compromised Lubrication	66
5.9.2. Combustible Foreign Materials	66
5.10. Improper Installation of Accessories and Modifications	67
5.11. Inappropriate Service	68
5.12. Aging and Random Failures	69
References	70

Chapter 06 - Water × Electricity

6.1. Introduction	71
6.2. Electrolysis/Electrolytic Corrosion/Dendritic Growth	72
6.2.1. Electrolysis	72
6.2.2. Electrolytic Corrosion	72
6.2.3. Dendritic Growth	73
6.3. IPXX	73
6.4. Sealing Degradation Mechanisms	74
6.4.1. Vibration and Mechanical Stress	74
6.4.2. Temperature Variations	74
6.4.3. Exposure to Chemicals and Corrosion	75
6.4.4. Improper Maintenance	75
6.4.5. Accidental Damage	75
6.4.6. Wear, Tear, and Aging	75
6.5. Capillarity	76
6.6. Pumping/Respiration	77
References	78

Chapter 07 - xEV Fundamentals

7.1. Introduction	79
7.2. Configurations and Acronyms	80
7.2.1. BEV	80
7.2.2. EV	82
7.2.3. FCEV or FCV	82
7.2.4. HEV	82
7.2.4.1. Micro HEV (MHEV)	84
7.2.4.2. Mild HV (MHV or mHEV)	84
7.2.4.3. (Full) HEV	84
7.2.4.4. Plug-In Hybrid Electric Vehicle (PHEV)	84
7.2.4.5. Series and Parallel Hybrids	86
7.2.5. ICE	86
7.2.6. ICV or ICEV	86
7.2.7. New Energy Vehicles (NEV)	87
7.2.8. Plug-In Electric Vehicle (PEV)	87
7.2.9. xEV	87
7.2.10. Zero-Emission Vehicle (ZEV)	87
7.3. Components	87
7.3.1. Electric Motor/Generator	87
7.3.2. Low-Voltage Battery	88

7.3.3. Traction Battery	88
7.3.4. Battery Management System (BMS)...	91
7.3.5. Supercapacitors	91
7.3.6. Onboard Recharger	92
7.3.7. High-Voltage Harness.....	92
7.3.8. High-Voltage Electronic Modules.....	93
7.3.9. Manual Service Disconnect (MSD).....	93
7.3.10. High-Voltage Disconnection	93
7.3.11. Fuel Cells	94
7.3.12. Hydrogen Tank	94
7.3.13. Regenerative Braking.....	94
7.4. Recharging Stations and Connectors	95
7.5. Inductive Rechargers	96
7.5.1. Inductive Rechargers without a Paddle.	96
7.5.2. Inductive Rechargers with a Paddle ...	96
References	97

Chapter 08 - xEV Specific Risks

8.1. Introduction	99
8.2. High Voltages	100
8.3. Lithium Battery.....	100
8.3.1. Safety and Optimal Operating Windows	100
8.3.2. Dendritic Growth	100
8.3.3. Thermal Runaway.....	101
8.3.4. Energy Released in a Fire	103
8.3.4.1. Heat from Electric Energy	103
8.3.4.2. Heat from Exothermic Reactions and Adjacent Cells	103
8.3.4.3. Heat from Burning Fuels	104
8.3.4.4. Fuels	104
8.3.4.5. Oxidizers	104
8.3.5. LIB Fire Triangle	104
8.4. Complexity	105
8.5. Manufacturing and Service	105
8.6. Recharging	106
8.7. Collisions	107
8.8. Flooding and Submersion	107
8.9. Toxic Gases and Jet Fires	108
8.10. Firefighting Challenges.....	109

8.11. Extrication Challenges	112
8.12. Reignition	112
8.13. (Toxic and Hazard Risks during) Fire Analysis.....	114
References	114

Chapter 09 - Fire Spread and Dynamics

9.1. Introduction	117
9.2. General Case/Structural Fires	117
9.3. Phases and Special Events.....	119
9.3.1. Fire Development Phases.....	119
9.3.1.1. Ignition Phase	119
9.3.1.2. Growth Phase	120
9.3.1.3. Fully Developed Phase	120
9.3.1.4. Decay or Extinction Phase	120
9.3.2. Special Events.....	120
9.3.2.1. Backdraft	120
9.3.2.2. Flashover	120
9.4. Automotive Environment Peculiarities.....	121
9.4.1. Vehicle Compartments	121
9.4.2. External Environment	121
9.4.3. Flammable Fluids	121
9.4.4. Plastic Content	121
9.4.5. Low-Voltage Battery.....	122
9.4.6. Traction Battery	122
9.4.7. Fire Duration.....	122
9.4.8. Spread to Neighboring Vehicles.....	123
9.5. Fires Initiated in the Engine Compartment	123
9.6. Fires Initiated in the Cabin.....	125
9.7. Pool Fires	126
9.8. Fires Initiated in the Traction Battery	127
9.9. Burn Patterns	129
9.9.1. Seat of Fire	129
9.9.2. V Pattern	130
9.9.3. Charring.....	130
9.9.4. Melting and Dripping.....	130
9.9.5. Damage to Wiring and Electric Components	131
9.9.6. Flow Path.....	131

9.9.7. Other Burn Patterns	131
9.9.8. Vehicle Components Affected	132
9.9.9. Multiple Origins.....	133
9.10. Wind Influence	133
9.10.1. Accelerating Fire Spread	134
9.10.2. Fire Direction and Path	134
9.10.3. Increased Heat Transfer	134
9.10.4. Smoke Spread and Visibility	135
9.10.5. Ember Transport.....	135
9.10.6. Fire Control and Suppression.....	135
9.11. Cars Always Explode in Movies	135
9.12. Parts That Might Explode	136
9.13. Cause: Chemical → Electrical or Vice Versa?.....	137
References	138

Section 2: Prevention

Chapter 10 - Product Design

10.1. Introduction	141
10.2. Product Design Strategies.....	142
10.2.1. Early Age and Conformance.....	142
10.2.2. Zero Defects and Continuous Improvement.....	142
10.2.3. Precision Engineering and Six Sigma ..	142
10.2.4. Computer-Aided Design (CAD).....	142
10.2.5. Integrated Product Development (IPD) ..	142
10.2.6. Sustainability and Efficiency	142
10.2.7. Advanced Technologies	142
10.3. Robust Design	143
10.4. Specifications and Regulations	144
10.5. Other Prevention Tools	145
10.6. Mechanical Barriers	146
10.7. Electrical Barriers	147
10.7.1. Fuses	147
10.7.2. Resettable Fuses	148
10.7.3. Relays	148
10.7.4. Bimetallic Thermal Switches.....	149
10.7.5. Smart Switches.....	149
10.7.6. Surge Suppressors.....	149
10.7.7. Electronic Architecture.....	149

10.8. Logical (Software) Barriers for xEVs	149
10.8.1. Battery System Management	150
10.8.2. Smart Chargers	150
10.8.3. Conductive Charger Immobilization.	150
10.8.4. Secure Charger Connection and Disconnection	150
10.8.5. Resilience to Failures	151
10.8.6. Emergency Battery Disconnection	151
10.9. Traction Battery Design Layers	151
References	151

Chapter 11 - Development and Maintenance

11.1. Introduction	153
11.2. V-Cycle	153
11.2.1. Left Side—Development Phase.....	154
11.2.1.1. Requirements Definition	154
11.2.1.2. System Design	154
11.2.1.3. Component Design	154
11.2.1.4. Implementation	154
11.2.2. Right Side—Verification and Validation Phase	154
11.2.2.1. Unit Testing	154
11.2.2.2. Integration Testing	154
11.2.2.3. System Testing	154
11.2.2.4. Validation Testing	154
11.2.2.5. Release and Maintenance	154
11.3. Simulations.....	155
11.3.1. Cost-Efficiency.....	155
11.3.2. Rapid Prototyping	155
11.3.3. Safety Testing	155
11.3.4. Performance Optimization.....	156
11.3.5. Environmental Impact	156
11.3.6. Regulatory Compliance	156
11.3.7. Early Issue Identification.....	156
11.3.8. Noise and Vibration Analysis	156
11.3.9. Testing Extreme Conditions	156
11.3.10. Design Verification.....	156
11.3.11. Human–Machine Interface (HMI)	156
11.3.12. Training and Education.....	156
11.4. Physical Validations	157
11.4.1. Real-World Verification.....	157

11.4.2. Unknown and Unpredictable Variables .	157	11.7.3. Complex Systems.	162
11.4.3. Complex Interactions.	157	11.7.4. Factory Floor Evaluations	163
11.4.4. Safety Assurance	158	11.7.5. Cost Control	163
11.4.5. Quality Assurance.	158	11.7.6. Quality Assurance.	163
11.4.6. Validation of Prototypes	158	11.7.7. Market Competitiveness.	163
11.4.7. Regulatory Compliance	158	11.7.8. Reputation and Brand Trust	163
11.4.8. Customer Satisfaction	158	11.7.9. Supplier Management	163
11.4.9. Benchmarking and Competitive Analysis.	158	11.7.10. Environmental Impact	163
11.4.10. Iterative Development.	159		
11.5. Product and Process Development Stages.	159	11.8. Maintenance.	164
11.5.1. Relevance of Product and Process Development Stages	159	11.8.1. Regular Inspections	164
11.5.1.1. Product Development Stages	159	11.8.2. Preventive Maintenance	164
11.5.1.2. Process Development Stages	159	11.8.3. Corrective Maintenance	164
11.5.1.3. Integration of Product and Process Development	159	11.8.4. Risks Associated with Neglect	164
11.5.2. Progressively Representative Prototypes and Processes	159	11.8.5. Electronic Diagnostics	164
11.5.2.1. Mules	159		
11.5.2.2. Pre-Series Prototypes	160	References	165
11.5.2.3. Mass Production Prototypes	160		
11.5.3. Customization of Development Stages. . .	160	Section 3: Analysis	
11.5.3.1. Each Automotive Manufacturer's Approach	160	Chapter 12 - Recommended Analysis Method	
11.5.3.2. Intermediate Phases	160	12.1. Introduction	169
11.5.3.3. Iterative Approach	160	12.2. Fire-Related Institutions.	170
11.6. Poka-Yoke.	160	12.3. The Search for the Cause	170
11.6.1. Quality Assurance.	161	12.4. Scientific Method	172
11.6.2. Cost Reduction	161	12.4.1. Precision.	172
11.6.3. Efficiency and Productivity	161	12.4.2. Evidence-Based.	172
11.6.4. Worker Safety.	161	12.4.3. Replicability	172
11.6.5. Regulatory Compliance	161	12.5. Step by Step.	172
11.6.6. Customer Satisfaction	161	12.5.1. Recognition of the Need	172
11.6.7. Complexity of Modern Vehicles	161	12.5.2. Problem Definition	172
11.6.8. Lean Manufacturing.	162	12.5.3. Data Collection	173
11.7. Risk Evaluations	162	12.5.4. Data Analysis.	173
11.7.1. Safety Assurance	162	12.5.5. Hypothesis Formulation (Inductive Reasoning)	173
11.7.2. Compliance with Regulations	162	12.5.6. Hypothesis Testing (Deductive Reasoning)	173
		12.5.7. Final Hypothesis Selection	173
		12.6. Words of Caution	174
		12.6.1. Avoid Presumption.	174
		12.6.2. Beware of Expectation Bias	174
		12.6.3. Beware of Confirmation Bias	174

12.7. Recommended Stages	174
12.8. Exceptions	176
12.8.1. Emergency Situations	176
12.8.2. Environmental Factors	176
12.8.3. Limited Resources	176
12.8.4. Legal and Practical Considerations	177
12.8.5. Complex Incidents	177
12.8.6. Human Behavior and Intent	177
12.8.7. Historical Data	177
12.8.8. Incomplete Information	177
12.9. Chain of Evidence	177
12.9.1. Evidence Collection	177
12.9.2. Documentation	178
12.9.3. Packaging and Labeling	178
12.9.4. Transportation	178
12.9.5. Receiving at the Laboratory	178
12.9.6. Laboratory Analysis	178
12.9.7. Storage	178
12.9.8. Documentation of Changes	178
12.9.9. Court Presentation	178
References	178

Chapter 13 - Data Collection and Analysis

13.1. Introduction	181
13.2. Safety	182
13.2.1. PPE	182
13.2.2. Fire Scene Hazards	182
13.2.3. Fire Residue Exposure	182
13.2.4. Explosive Hazards	182
13.2.5. Electrical Hazards	182
13.2.6. Environmental Considerations	182
13.2.7. Communication and Emergency Planning	183
13.2.8. Training and Experience	183
13.2.9. Legal and Regulatory Compliance	183
13.2.10. Decontamination	183
13.3. Preliminary Data	183
13.4. Preparation	184

13.5. Field Kit	184
13.6. Checklist	185
13.7. Field Analysis	187
13.7.1. Safety Reminder	187
13.7.2. Fire Scene Preservation	187
13.7.3. Documentation	187
13.7.4. Surveillance Cameras	188
13.7.5. Evidence Collection	188
13.7.6. Assessment of Interventions	188
13.7.7. Assessment of the Environment for Deliberate Acts	189
13.7.8. Before You Leave the Scene	189
13.8. Vehicle Analysis	189
13.8.1. Safety Reminder	190
13.8.2. Photography Protocol	190
13.8.3. Vehicle Identification	191
13.8.4. Vehicle Body	191
13.8.5. Fuel System	191
13.8.6. Engine and Transmission	191
13.8.7. Exhaust System, Catalytic Converters, Turbochargers, and EGR	191
13.8.8. Electric system	191
13.8.9. Evidence of Short Circuits	192
13.8.10. Braking System	192
13.8.11. Potentially Intentional Acts/Arson	193
13.8.12. Airbag and Restraint Systems	193
13.8.13. Missing Parts	193
13.8.14. Other/Miscellaneous	194
13.8.15. xEVs	194
13.8.15.1. High-Voltage Components	194
13.8.15.2. LIBs	194
13.8.15.3. Thermal Runaway	195
13.8.15.4. Chemical Hazards	195
13.8.15.5. Supercapacitors	195
13.8.15.6. Hidden Fires	195
13.8.16. Apparent Fire Dynamics	195
13.8.17. Before You Leave the Vehicle	195
13.9. Postfield and Vehicle Analysis	196
References	196

Chapter 14 - Hypotheses Development and Testing

14.1. Introduction	.197
14.2. Hypotheses Categories	.198
14.2.1. Start Location Hypotheses	198
14.2.2. Root Cause Hypotheses	198
14.2.2.1. Typical Hypotheses	198
14.2.2.2. Electrical or Nonelectrical Hypotheses	199
14.2.3. Accidental/Intentional Hypotheses	199
14.3. Developing Hypotheses	.200
14.4. Testing Hypotheses	.200
14.4.1. Evidence That Rejects Fuel/Thermal Causes	201
14.4.2. Evidence Suggestive of Fuel/Thermal Causes	201
14.4.3. Evidence That Rejects Electric Causes	201
14.4.4. Evidence Suggestive of Electric Causes	201
14.4.5. Evidence Suggestive of Design Errors	201
14.4.6. Evidence Suggestive of Manufacturing Errors	201
14.4.7. Evidence Suggestive of Service Errors	202
14.5. Ideal and Unexpected Outcomes	.202
14.5.1. All Hypotheses Rejected	202
14.5.2. Too Many Hypotheses Remain Viable	203
14.5.3. Two or Three Hypotheses Remain Viable	203
14.6. Reevaluate, Adjust, and Retest	.204
14.7. Finalize Conclusions	.204
14.8. Peer Review	.204
14.9. Legal and Regulatory Considerations	.205
References	.205

Chapter 15 - Case Studies

15.1. Introduction	.207
15.2. Case A: Engine Compartment Fire	.208
15.2.1. Information Available Before Vehicle Analysis	208

15.2.2. Preliminary Hypotheses	208
15.2.2.1. Starting Point	208
15.2.2.2. Cause	208
15.2.2.3. Intent	208
15.2.3. Key Findings during Vehicle Analysis and Owner's Interview	208
15.2.4. Main Photos	209
15.2.5. Hypotheses Testing	213
15.2.5.1. Starting Point	213
15.2.5.2. Cause	213
15.2.5.3. Intent	213
15.2.6. Conclusion	213
15.2.6.1. Starting Point	213
15.2.6.2. Cause	213
15.2.6.3. Intent	214

15.3. Case B: Engine Compartment Fire214

15.3.1. Information Available before Vehicle Analysis	214
15.3.2. Preliminary Hypotheses	214
15.3.3. Key Findings during Vehicle Analysis and Owner's Interview	214
15.3.4. Main Photos	215
15.3.5. Hypothesis Testing	218
15.3.6. Conclusion	219

15.4. Case C: Truck Tractor Fire220

15.4.1. Information Available before Vehicle Analysis	220
15.4.2. Preliminary Hypotheses	220
15.4.3. Key Findings during Vehicle Analysis and Driver's Interview	220
15.4.4. Main Photos	221
15.4.5. Hypothesis Testing	226
15.4.6. Conclusion	226

15.5. Case D: Semitrailer Tire Fire227

15.5.1. Information Available before Vehicle Analysis	227
15.5.2. Preliminary Hypotheses	227
15.5.3. Key Findings during Vehicle Analysis	227
15.5.4. Main Photos	228
15.5.5. Hypothesis Testing	230
15.5.6. Conclusion	230

15.6. Case E: BEV Fire after Running over
Debris231

15.6.1. Information Available before Vehicle
Analysis.231

15.6.2. Key Findings during Vehicle Analysis. . .231

15.6.3. Main Photos232

15.6.4. Conclusion234

References235

Bibliography237

Acronym Glossary239

Index243

About the Author.249