

# **The handbook of tunnel fire safety**

**Edited by**

*Alan Beard and Richard Carvel*

# Contents

Preface, <i>Alan Beard and Richard Carvel</i>	iii
Biographies	iv
Introduction: tunnel fire safety decision-making and knowledge, <i>Alan Beard</i>	xvii
<b>Part I. Real tunnel fires</b>	<b>1</b>
<b>1. A history of fire incidents in tunnels</b>	<b>3</b>
<i>Richard Carvel and Guy Marlair</i>	
Introduction	3
Fires in road tunnels	4
Fires in rail tunnels	6
Concluding comments	8
A history of tunnel fire incidents	9
Acknowledgements	37
References	37
<b>2. Tunnel fire investigation I: The Channel Tunnel fire, 18 November 1996</b>	<b>42</b>
<i>Martin Shipp</i>	
Introduction	42
The Channel Tunnel fire	42
The tunnel system	42
The fire safety system	43
The incident	44
The investigation	44
Method	46
Findings from the incident	48
Issues, problems and lessons for fire investigation	49
Discussion	50
Conclusions	51
Acknowledgements	51
Abbreviations	51
Appendix 2.1. Background of the CTSA	51
References	52
<b>3. Tunnel fire investigation II: The St Gotthard Tunnel fire, 24 October 2001</b>	<b>53</b>
<i>Jean-Claude Martin, Olivier Delémont and Claude Calisti. Translated by R. Carvel</i>	
Introduction	53
Incident summary	53
Aims of the investigation into the fire and explosion	55
Summary description of the incident zone	55
Chronology of the incident	60
Discussion of the chronology	60
The origin of the fire	60

Cause of fire	64
Propagation of the fire across HGVs 1 and 2	71
Spread of the fire to HGVs 3 to 7	72
Thermal degradation on the vehicles beyond HGV 7	73
General discussion	74
Conclusions	74
Appendix 3.1. Important factors relating to the investigation of a fire in a road tunnel	75
<b>Part II. Prevention and protection</b>	<b>77</b>
<b>4. Prevention and protection: general concepts</b>	<b>79</b>
<i>Alan Beard</i>	
Introduction	79
Risk as a systemic product	79
Hazard and risk	81
Prevention and protection as basic concepts	82
Context and causation	83
Prevention and protection in tunnels	83
Fire safety management	86
Fire prevention	87
Fire protection	87
Summary	88
Appendix 4.1. Thoughts on avoiding major tunnel fires ( <i>Paul Scott</i> )	89
References	92
<b>5. Fire detection systems</b>	<b>93</b>
<i>Sandro Maciocia</i>	
Introduction	93
Problems of detecting fires	93
Performance requirements for fire detection systems	98
Different approaches to alerting tunnel users	100
Currently available line-type heat fire detectors	101
Assessing state-of-the-art fire alarm systems	103
Future trends and emerging new technologies	105
Conclusions	108
References	109
<b>6. Fire protection in concrete tunnels</b>	<b>110</b>
<i>Richard Carvel</i>	
Introduction	110
Types of tunnels	111
The behaviour of concrete subject to fire	111
Passive fire protection	113
Active fire protection	119
A proposed alternative fire suppression system	122
Concluding comment	123
References	124
<b>7. Tunnel ventilation – state of the art</b>	<b>127</b>
<i>Art Bendelius</i>	
Introduction	127
Types of ventilation system	128

Ventilation system components	134
Facilities	137
Technology	137
The future	140
References	140
Additional reading	143
<b>8. Use of tunnel ventilation for fire safety</b>	<b>144</b>
<i>Stuart Jagger and George Grant</i>	
Introduction	144
Modes of operation of tunnel ventilation systems during a fire	146
Influence of ventilation on tunnel fire characteristics	157
Modelling tunnel flows	165
Conclusions	176
References	178
<b>9. The influence of tunnel ventilation on fire behaviour</b>	<b>184</b>
<i>Richard Carvel and Alan Beard</i>	
Introduction	184
Basic fire science	184
Definitions	186
Methodology	187
A note on naturally ventilated tunnel fires	188
Results	189
Discussion	195
Conclusions	196
Acknowledgements	197
References	197
<b>Part III. Tunnel fire dynamics</b>	<b>199</b>
<b>10. A history of experimental tunnel fires</b>	<b>201</b>
<i>Richard Carvel and Guy Marlair</i>	
Introduction	201
Fire experiments to gain understanding of fire phenomena	201
Fire experiments to evaluate sprinkler performance	212
Fire experiments to test or commission tunnel installations	213
Fire tests in operational tunnels	215
Experimental testing on a smaller scale	218
Laboratory-scale experiments	221
Non-tunnel fire experiments	224
Concluding comment	226
Further information	227
References	227
<b>11. Fire dynamics in tunnels</b>	<b>231</b>
<i>Haukur Ingason</i>	
Introduction	231
Tunnel fires and open fires	231
Tunnel fires and compartment fires	232
Fuel control and ventilation control	237

Stratification of smoke in tunnels	241
Average flow conditions in longitudinal flow	245
Determination of HRRs in tunnel fires	252
Flame length	254
Large fires in tunnels with longitudinal flow	258
Fire spread in tunnels	259
Nomenclature	262
References	263
<b>12. CFD modelling of tunnel fires</b>	<b>267</b>
<i>Norman Rhodes</i>	
Introduction	267
Mathematical overview	268
Physical phenomena in tunnel fire situations	271
Application of CFD techniques to tunnel fires	271
Validation and verification	274
Case study: The Memorial Tunnel experiments	275
Concluding remarks	282
Notation	282
References	282
<b>13. Control volume modelling of tunnel fires</b>	<b>284</b>
<i>David Charters</i>	
Introduction	284
Application of control volumes to tunnel fires	284
Application of control volume models to tunnel fire safety	290
Summary	297
References	297
<b>14. Problems with using models for fire safety</b>	<b>299</b>
<i>Alan Beard</i>	
Introduction	299
Models and the real world	300
Kinds of theoretical models	303
Models as part of tunnel fire safety decision making	306
Illustrative case	308
The potential of a specific model in tunnel fire safety decision making	313
An acceptable 'methodology of use'	313
A 'knowledgeable user'	314
Evacuation modelling	315
Conclusions	315
References	317
<b>Part IV. Fire safety management and human factors</b>	<b>321</b>
<b>15. Human behaviour in tunnel fires</b>	<b>323</b>
<i>Jim Shields</i>	
Introduction	323
Some recent tunnel fires	323
Towards understanding human behaviour in tunnel fires	329
Responding to a developing emergency	338

Recent developments	338
Concluding remarks	339
References	341
<b>16. Recommended behaviour for road tunnel users</b>	<b>343</b>
<i>Michel Egger</i>	
Introduction	343
Safety and risks in road traffic	344
Safety objectives in road tunnels	345
Road users as a factor influencing safety in road tunnels	347
Proposed measures for road users	349
Conclusions and outlook	353
References	353
<b>17. Transport of hazardous goods</b>	<b>354</b>
<i>Emmanuel Ruffin, Philippe Cassini and Hermann Knoflacher</i>	
Introduction	354
<i>Section I: Road tunnels</i>	354
The situation concerning the road transport of hazardous goods in the European Union	354
Harmonised groupings of dangerous goods	355
Quantitative risk assessment model	366
Risk reduction measures for road tunnels	374
Member states' experiences of the QRAM	376
<i>Section II: Rail transport and road/rail intermodality</i>	381
The situation concerning the rail transport of hazardous goods in the EU	381
The situation in the professional engineering world for rail transport	382
A new QRA model for rail	383
Conclusions	385
References	386
<b>18. A systemic approach to tunnel fire safety management</b>	<b>388</b>
<i>Jaime Santos-Reyes and Alan Beard</i>	
Introduction	388
A Tunnel Fire Safety Management System model	389
Fire safety performance	399
The MRA, the acceptable range of fire risk and the viability	403
Conclusion	403
Appendix 18.1. The four organisational principles	404
Appendix 18.2. Control and communication paradigms	405
References	406
<b>19. Road tunnel operation during a fire emergency</b>	<b>408</b>
<i>John Gillard</i>	
General introduction	408
The stakeholders in tunnel safety	409
The factors that influence tunnel operational safety	410
The nature of incidents	412
Liaison between tunnel operator and emergency services	414
Incident response	416
Decisions and actions	417

<b>20. Tunnel fire safety and the law</b>	<b>422</b>
<i>Arnold Dix</i>	
Introduction	422
Legal investigations follow incidents	422
Legal investigations scrutinise past decisions	428
Conclusions	433
References	433
<b>Part V. Emergency procedures</b>	<b>435</b>
<b>21. Emergency procedures in road tunnels: current practice and future ideas</b>	<b>437</b>
<i>David Burns</i>	
Introduction	437
Managing safety in tunnels	437
Contingency planning	441
Equipment provision	445
Location of emergency response teams	445
Rapid response teams	446
Incident management	446
Integration of design and management with emergency response	447
Conclusions	449
References	450
<b>22. Emergency procedures in rail tunnels: current practice and future ideas</b>	<b>451</b>
<i>John Olesen</i>	
Introduction	451
Standard operational procedures?	451
Contingency planning	457
Considerations	465
Education, training	468
Conclusions	473
A detailed example: emergency procedures in the Great Belt Tunnel, Denmark	473
<b>23. Fire and rescue operations in tunnel fires: a discussion of some practical issues</b>	<b>481</b>
<i>Anders Bergqvist, Håkan Frantzich, Kjell Hasselrot and Haukur Ingason</i>	
Introduction	481
Reference assumptions	481
An accident has occurred and rescue work is in progress	482
Breathing apparatus operations in complicated environments	484
Extinguishing extensive fires in tunnels	486
The rescue work continues	487
What are the main problems in dealing with a fire and rescue situation in a tunnel and how can they be solved?	489
Conclusions	503
References	504
<i>Index</i>	505