The handbook of tunnel fire safety

Edited by
Alan Beard and Richard Carvel
Preface

This is the first ever Handbook of tunnel fire safety. That it has appeared at this time is in part a reflection of the considerable growth in tunnel construction worldwide and in part a reflection of concern in society about tunnel safety and fire safety in particular. While much research has been carried out on tunnel fire safety over the years, a text bringing together basic knowledge over a broad spectrum has not existed. This Handbook makes a first effort at filling this gap. It is intended for all those involved in tunnel fire safety, from fire brigade personnel who are at the sharp end when a tunnel fire occurs, to tunnel designers and operators as well as researchers. While the different chapters address different aspects, it is intended that a central theme should run through the book; that is, the need to see fire risk as a product of the working of a system. It follows from this that considerations of emergency planning and design against fire need to be in at the beginning of the design stage; the philosophy of regarding fire safety measures as a ‘bolt on’ after a design has largely been completed is now totally unacceptable, especially in light of the ever longer and more complex tunnels that are now being built or planned. Within this context, this text hopes to be a bridge between tunnel fire research and those who need to know basic results, techniques and current thinking in decision-making with respect to tunnel fire safety. Beyond that, it is also a vehicle for the transmission of contemporary thinking in the subject.

The Handbook covers a broad span of knowledge and, consistent with this, authorities in the various fields have written the different chapters. The chapter titles and contents reflect the range of work which has been conducted in the past. Much research remains to be done, however. For example, currently we know very little about human behaviour in tunnel fires. Also, preventing fires occurring in tunnels as opposed to trying to protect after fire exists needs much more consideration. Further, the general move towards a performance-based decision-making philosophy implies probabilistic concepts; much more needs to be done here. This also relates to the question of what is to be regarded as ‘acceptable risk’ in relation to tunnel fires. Much consideration and debate needs to take place in this area, including all those involved and affected. This first Handbook is intended to represent the broad sweep of knowledge at the present time; the chapter authors are international experts in their own fields. The time is ripe for such a volume and it is hoped that it will become a valuable resource for all those concerned with tunnel fire safety.

Alan Beard
Richard Carvel
Edinburgh, April 2004
Biographies

ALAN BEARD, Reader in Fire Safety Engineering, Civil Engineering Section, School of the Built Environment, Heriot-Watt University, Edinburgh, UK.

Alan Beard studied Physics at Leicester University and in 1972 was awarded a PhD in Theoretical Physics from Durham University. He is a Chartered Mathematician and Member of the Institute of Mathematics and its Applications as well as of the Institution of Fire Engineers. After carrying out research in medical physics at Exeter University and the University of Wales, in 1977 he started fire research at Edinburgh University, leaving in 1995 to go to Heriot-Watt University, Edinburgh, where he has been Reader in Fire Safety Engineering since 2003. His research is in the very broad area of modelling in relation to fire safety; including deterministic and probabilistic modelling as well as qualitative research, in particular applying the concepts of systems to safety management. His research has covered fire safety in buildings, offshore installations and railways. Since 1993, a major research interest has been in the field of tunnel fires. He has conducted research for both government departments and industrial companies. Further, his papers have been used as key references by the International Standards Organization and some of his research has been translated into Japanese. More generally, he is concerned to help to develop a framework for the acceptable use of fire models in fire safety decision-making.

ARTHUR G. BENDELIUS, Associated Consultant, Parsons Brinckerhoff, Quade & Douglas, USA.

Arthur Bendelius served as Senior Vice President, Principal Professional Associate and Technical Director for Tunnel Ventilation with Parsons Brinckerhoff. He currently serves as Parsons Brinckerhoff’s Technical Director for Tunnel Ventilation. His technical background is in mechanical systems, particularly tunnel services such as ventilation, fire protection and drainage systems. He currently serves as the most recent Chair of the NFPA Road Tunnel and Highway Fire Protection Technical Committee (which is responsible for ‘NFPA 502 Standard for Road Tunnels, Bridges and Other Limited Access Highways’) and is a Member of the NFPA Fixed Guideway Transit Systems Technical Committee (responsible for ‘NFPA 130 Standard for Fixed Guideway Transit and Passenger Rail Systems’). He currently is a Member of the World Road Association (PIARC) – Technical Committee C-5 3.3 ‘Road Tunnel Operation’ and serves as Animateur of PIARC Working Group No 6 on Fire and Smoke Control in Road Tunnels. He also continues to serve as a Member of ASHRAE Technical Committee TC 5.9 ‘Enclosed Vehicular Facilities’. He has authored over 30 technical papers and professional articles and is one of the contributing authors to the Tunnel Engineering Handbook, the ASHRAE Handbook on Applications and the Fire Protection Handbook. He has a BE degree and a MMS degree from Stevens Institute of Technology. He is a Fellow of the American Society of Heating, Refrigerating and Air-Conditioning Engineers and the Society of American Military Engineers. He is also a Member of the British Tunneling Society. He is a Registered Professional Engineer.

ANDERS BERGQVIST, Senior Division Officer and Fire Safety Engineer, Stockholm Fire Brigade, Sweden.

Anders Bergqvist has been a Senior Division Officer and Fire Safety Engineer in Stockholm Fire Brigade since 1997. During 2001–2002 he worked as Head of Section at SP Swedish National Testing and Research Institute. Before he started working in Stockholm, he worked as a teacher for the National Rescue Service Agency, with fire safety for the Swedish Navy and as a fire fighter for
Prince Georges Fire Department (USA). He is a Fire Safety Engineer from the University of Lund and is a Member of the Society of Fire Protection Engineers, Swedish chapter. He works both with the operational fire and rescue service and with fire prevention, and during the last seven years he has worked with fire prevention and contingency planning for fire and rescue operations in tunnels.

DAVID BURNS, Assistant Chief Fire Officer, Merseyside Fire Service, UK.

David Burns is an Assistant Chief Fire Officer with Merseyside Fire Service in the UK and has served in several metropolitan fire services in the UK. He has been a professional firefighter for 26 years. He is a Member of the European Fire Services Tunnels Group and has presented papers on the subject of tunnel fire safety and emergency management at national and international conferences.

CLAUDE CALISTI, Chief of the Fires and Explosives Department of the Laboratoire Central of the Prefecture de Police de Paris, France.

Claude Calisti obtained a Licence es Sciences, option Chemistry (old regime) in 1961 at the University of Marseille-Provence, France. From 1962 to 1965, he was Moniteur and then Delegate Assistant in General Chemistry (Professor Edouard Calvet). In 1965, he became an Engineer in the Service of Explosives at the Laboratoire Central of the Prefecture de Police de Paris (LCPP); he participated at de-mining operations and technical enquiries after fires, explosions and attacks perpetrated with explosives. In 1976, he was promoted to Chief Engineer in the Service of Explosives of the LCPP and in 1999 he became the Chief of the fires and explosives department of the LCPP. Since 2002, he has acted as Scientific Counsellor for Madame la Préfète, General Secretary of the ‘defense’ zone of Paris. He has been an Expert for the Court of Appeal of Paris since 1973, recognised by the Cassation Court since 1981 (specialities: explosives, explosions and fires). He has been a Member of many national commissions (de-mining, explosives, AFNOR) and of work groups at the Ministère de l’Intérieur and Ministère de l’Aviation civile and has participated in several international seminars and meetings.

RICHARD CARVEL, Research Associate in Fire Safety Engineering, University of Edinburgh, UK.

During his time as a Research Associate at Heriot-Watt University (1998 to 2004) Richard Carvel studied tunnel fire phenomena and was awarded a PhD for his thesis *Fire Size in Tunnels* in 2004. He has established an international reputation in the field of tunnel fire safety through numerous presentations at international tunnel safety and fire symposia. Before his studies on tunnel fires, he spent four years studying dust detonations at the Centre for Explosion Studies, University of Aberystwyth. He is a graduate of St Andrews University, obtaining a BSc (Hons) in Chemistry and Physics in 1992 and an MPhil in Chemistry in 1994. He has also worked as a Consultant with International Fire Investigators and Consultants (IFIC), Glasgow.


Philippe Cassini graduated as an Engineer from the Ecole Centrale de Lyon in 1975. After graduation, he worked for six years for the French underground coal mines. Then he started to work at the Centre d’Etudes et Recherche des CHARbonnages de France (CERCHAR), where he studied the ambient conditions in deep mines. In 1991, he took the position of Manager of the industrial ventilation laboratory. He has been involved in many projects concerning fire safety in tunnel and underground network ventilation. He also studied the safety issues of some major tunnel projects (Gotthard, Lotschberg). In 1994 he developed a first version of a new tool for the Quantitative Risk Assessment of the road transportation of dangerous goods. In 1997–1999, he was the leader of a consortium which delivered a second completed version (OCDE/PIARC project ERS2). In 2000 he became Team Manager for major risk evaluations in the Accidental Risk Division (DRA). He has been an Expert Member of the French National Comity for Safety in Road Tunnels which was created after the Mont Blanc catastrophe. He is presently Technical Co-ordinator for the public funded actions of INERIS.
DAVID CHARTERS, Director and Group Leader, Arup Fire, Leeds, UK.

David Charters is a chartered Fire Engineer with a doctorate in fire growth and smoke movement in tunnels. He is Visiting Professor at the University of Ulster (FireSERT), Chair of British Standards Committee FSH/24 Fire Safety Engineering, and International President Elect of the Institution of Fire Engineers. Recent experience includes new and existing tunnels for MTRC and Network Rail, Channel Tunnel Rail Link, Dublin Port Tunnel and New Tyne Crossing. In addition, he was heavily involved in the rail industry fire safety and risk assessment after the King’s Cross fire disaster in 1987.

OLIVIER DELE´MONT, Senior Lecturer at the Institut de Police Scientifique et de Criminologie of the University of Lausanne, Switzerland.

Olivier Dele´mont graduated in forensic sciences at the Institut de Police Scientifique et de Criminologie (IPSC) of the University of Lausanne, Switzerland, in 1996. Since then, he has worked at this institute as Scientific Collaborator, performing simultaneously research, educational and judicial expert assessment activities. Since 2003, he has also worked part-time in the technical and scientific service of the Geneva state police as a Criminologist. In 2004, he was promoted to Senior Lecturer at the Institut de Police Scientifique and completed his PhD in research concerned with fire investigation and fire modelling. At present he is continuing his work in the technical and scientific service of the police and in the Institut de Police Scientifique of the University of Lausanne.

ARNOLD DIX, Adjunct Professor of Engineering at Queensland University of Technology, Australia.

Arnold Dix is formally qualified as both a scientist and a lawyer. He was appointed Adjunct Professor of Engineering at Queensland University of Technology in early 2004. He is Australia’s delegate for PIARC (a United Nations affiliate inter-governmental organisation) on the fire and life safety in tunnels working group. He also Heads the International Tunnelling Association’s Contractual Practices group and is Secretary to their security group. He advises both governments and corporations on the management of underground transport infrastructure risks and is actively involved in projects around the world.

MICHEL EGGER, Secretary General of the Conference of European Directors of Roads, France.

Michel Egger graduated as a Civil Engineer in 1972 from the Federal Institute of Technology in Zurich. He then worked for construction companies managing a wide range of projects in Europe, Africa and the Middle East. From 1999 to 2004 he was Deputy Director and Chief of the Road Infrastructure Division of the Federal Road Authorities, Bern, Switzerland where he was responsible for the construction, maintenance and operation of the Swiss national road network. He was a Federal Delegate during the reconstruction of the Gotthard Tunnel after the fire of 2001 and President of the international group of experts on safety in tunnels for the United Nations Economic Council for Europe (UN-ECE) in Geneva. From 2004 he has been Secretary General of the Conference of European Directors of Roads (CEDR), Paris, France. CEDR comprises 25 European directors who deal with all aspects of roads and road transport. He is President of the Strategic Plan ad hoc Group defining the priorities for the actions of CEDR.

HÅKAN FRANTZICH, Senior Lecturer, Department of Fire Safety Engineering, Lund University, Sweden.

Håkan Frantzich has a degree in Fire Protection Engineering from the Department of Fire Safety Engineering, Lund University, and a PhD in Fire Safety Engineering Risk Analysis. After the PhD he continued working for the Department as a Researcher and is at present a Senior Lecturer. He has mainly been working in the area of safety during evacuation. Reports which he has produced cover both human behaviour and movement of people during fire and evacuation. He took a licentiate degree in 1994 in this area. During the past few years he has been more involved in projects where the
risk to people is evaluated. His recent research covers aspects such as dominant factors contributing to successful evacuation and risk index methods for health care facilities. He is also involved in developing rational verification procedures for Fire Safety Engineering design.

JOHN GILLARD, General Manager, Mersey Tunnels, UK.

John Gillard holds an honours degree in Civil Engineering, is a Chartered Engineer and a Member of the Institution of Civil Engineers. After graduation, he spent two and a half years in academic research in the field of fluid dynamics. He then moved into the construction industry and spent ten years designing and building a wide range of works, including stormwater drainage, motorways, urban infrastructure, industrial and petrochemical complexes and airports in the UK and throughout Africa. He moved into the field of engineering operation and maintenance in 1982, initially airports and subsequently road tunnels. He has worked for Mersey Tunnels for 19 years, 14 of which have been as General Manager. He has been a Member of the Technical Advisory Committee for a number of international conferences series since 1991 and has written several papers on Tunnels Safety and Tunnels Management and Operation.

GEORGE GRANT, Safety Engineering Group, Halcrow Group Ltd, Stockton-on-Tees, UK.

George Grant has 20 years’ research and commercial experience in various aspects of fire safety engineering. After graduating in Civil Engineering at Dundee University, his PhD research concerned the problem of fires in railway tunnels. Joining Mott MacDonald in 1987, he worked on the design of the ventilation systems for the Channel Tunnel before embarking on a seven-year post-doctoral tenure at the University of Edinburgh’s Unit of Fire Safety Engineering. In 1998, he established his own consultancy business and worked with Eurotunnel on the development of the Onboard Fire Suppression System Project for HGV shuttle trains. He joined Halcrow Group in 2004 and continues to work on challenging projects within the newly-formed fire safety engineering group.

KJELL HASSELROT, BBm Fireconsulting, Bromma, Sweden.

Kjell Hasselrot worked as a fire fighter for Stockholm Fire Brigade for 25 years. He has also been involved in the training of fire fighters. He started his own company, BBm Fireconsulting, Bromma, in 1998.

HAUKUR INGASON, SP Swedish National Testing and Research Institute, Borås, Sweden.

Haukur Ingason has over ten years’ international experience in fire research. He has worked and studied in the USA, Europe and Scandinavia and obtained a PhD degree at the Technical University in Lund, Sweden. He has published over 30 scientific papers and reports on different subjects concerning fire safety. His present working place, the Swedish National Testing and Research Institute (SP), is one of a very few institutes in the world with recognised expertise in the subject area of fire safety. In 1994 he was the Chairman of the First International Conference on Fire Safety in Tunnels held at SP. He has been involved in large-scale and model-scale studies of fire and smoke spread in tunnels and a number of advanced consulting projects on tunnel fire safety. His main contributions to the fire safety community of tunnel safety are in the areas of design fires, smoke movement, visibility in smoke and the influence of ventilation on fire development.

STUART JAGGER, Head of the Health and Safety Laboratory, Buxton, UK.

Stuart Jagger studied Physics at Imperial College, London before going on to complete a PhD in Space Physics. After periods at Leeds and Reading Universities conducting post-doctoral research on satellite remote sensing, he joined the Atomic Energy Authority’s Safety and Reliability Directorate where he worked to develop models for the dispersion of dense gas clouds and source terms of releases of hazardous gases and liquids on chemical plant. In 1987 he joined the Health & Safety Executive’s Research and Laboratory Services Division (now the Health & Safety Laboratory – HSL) to work in the Fire Safety Section of which he is now Head. During his time at HSL he has
been involved in the study of hazards from a number of industrial fire situations including chemical warehousing, tunnels, offshore and nuclear facilities. He has also been involved in and directed several large incident investigations including those at Ladbroke Grove, in the Channel Tunnel, Grangemouth and King’s Cross Underground Station. For his work on the latter he was jointly awarded the ImechE’s Julius Groen Prize with his colleague Keith Moodie.

HERMANN KNOFLACHER, Chair in Transport Planning and Traffic Engineering, Technical University of Vienna, Austria.

Hermann Knoflacher has a Civil Engineering degree from the University of Vienna (1963), a Natural Science degree also from the University of Vienna (1965) and a PhD in Transportation Engineering. He left the University in 1968 and established the Institute of Transport Science, in the Austrian Transport Safety Board. He was Head of this Institute until 1985 and was responsible for several books and studies on transportation planning, traffic safety and human behaviour. Since 1972 he has been a Lecturer at the University of Technology in Vienna for traffic engineering. In 1971 he established a consulting company, which carried out most of the transport plans for Austrian cities, Austrian states, and national and international bodies, and more than 200 research projects. He has been engaged in tunnel safety since 1971 and was Advisor to the Minister for over eight years during the seventies and eighties. In 2001 he was asked to Chair the commission to enhance the traffic safety of Austrian tunnels. He is a Member of several national and international science and engineering organisations and the author of over 500 publications on transport planning, traffic safety and transport policy.

SANDRO MACIOCIA, Formerly Project Engineer, Area Sales Manager and Export Sales Manager, Securiton AG, Switzerland.

Sandro Maciocia holds an Electrical Engineer Diploma in Industrial Electronics and Technology of Energy, obtained at the Engineering School of Basle in Muttenz, Switzerland in 1990. He worked for two years as a Project Engineer on the electrical equipment of rolling stock and for nine years was a Project Engineer, Area Sales Manager and Export Sales Manager for Securiton AG in the field of alarm systems applications. He specialises in fire alarm system engineering in tunnel applications; he has both theoretical and practical experience in design, installation, testing and assessment of fire alarm systems.

GUY MARLAIR, Institut National de l’Environnement Industriel et des Risques (INERIS), France.

Guy Marlair was born in Brussels in 1957 and received his major education in France, completed by a diploma in Engineering. He started his professional career in the field of Fluidised Bed Combustion. He has been working for the past 14 years as a fire expert at INERIS. He has achieved considerable experience in a variety of technical domains associated with fire safety at an international level, including the use and development of fire testing, fire toxicity issues, fire hazard assessment in warehouses and tunnels, and experimental studies of chemical fires. He has very recently taken part in two EC funded projects related to tunnel fires safety, named FIT and UPTUN, and was also involved in the EUREKA 499 project on a related topic. He has authored or co-authored some 40 papers in journals, conferences and books on fire safety. He is also active in several standardisation committees (ISO TC92 SC3 and SC4, CEN TC114 WG 16, Chair of AFNOR X65A), and is a Member of the IAFSS. He is a Lecturer in several training centres and is currently working as a Program Leader on ‘Energetic Materials’ and related explosion and fire safety issues.

JEAN-CLAUDE MARTIN, Honorary Professor at the Institut de Police Scientifique et de Criminologie of the University of Lausanne, Switzerland.

Jean-Claude Martin graduated in Forensic Sciences and Criminology at the University of Lausanne, Switzerland in 1967. From there, he pursued in parallel the careers of Chemistry Teacher in a high school and Criminalist in the forensic service of the police. In 1991, he obtained a PhD in Forensic
Sciences, in the subject of fire investigation, at the Institut de Police Scientifique et de Criminologie (IPSC) of the University of Lausanne and became Scientific Collaborator in this institute. Since then he has led a research group in fire investigation and conducted many judicial expert assessments in the IPSC. In 1994, he was promoted to Associate Professor at the IPSC before becoming Honorary Professor at the same institution in 2002.

JOHN OLESEN, Chief Fire Officer, Korsør Fire Brigade, Denmark.

John Olesen has been involved in tunnel safety for more than a decade and is responsible for the exercises that are carried out every year in the tunnels with up to 1000 participants. He has been involved in the making and implementing of plans, communication strategy, cost-benefit systems etc. in tunnels. He has been educated as an Officer in the air force, the national and the municipal emergency services and is a frequent speaker at international conferences and also a member of international tunnel groups.

NORMAN RHODES, Project Manager, Hatch Mott MacDonald, USA.

Norman Rhodes is one of the world’s leading experts in the application of advanced engineering analysis to solve complex design problems. He has extensive knowledge and experience of the application of simulation techniques for engineering design and is an international expert in the use of computational fluid dynamics, having applied these techniques extensively in the design of normal and emergency ventilation systems, analysis of the aerodynamics of trains in tunnels and the prediction of smoke movement and fires in tunnels and buildings. His experience extends from the development and application of the very first general-purpose Computational Fluid Dynamic (CFD) models for three-dimensional ventilation and fire analysis to their present-day application in design. He is the Secretary of the PIARC Working Group on Fire and Smoke Control in Tunnels, and is a co-author of their publication Fire and Smoke Control in Road Tunnels. He also serves on the steering committee of the European Community Fires in Tunnels Thematic Network and is responsible for the preparation of best practice guidelines for emergency response management.

EMMANUEL RUFFIN, Program Manager, Institut National de l’Environnement Industriel et des Risques (INERIS), France.

Emmanuel Ruffin’s academic career comprises Fluid Mechanics and Aeronautics Engineering studies at the University of Marseilles (1990) and a PhD in 1994 also in Marseilles (thesis on Study of variable density turbulent jets using second order models (RANS)). From 1994 he was a Researcher at INERIS, involved in explosion, dispersion and fire theastics in the open air as well as in confined spaces. In those various fields he at first played a major part in experimental studies. Some of these applications were devoted to the design and measurement of safety ventilation equipment for underground nuclear waste sites and process industries. In parallel he produced a new model for the evaluation of explosion pressure waves, named EXPLOJET which can be used to complement the Multi-Energy and TNT methods for flammable jet clouds. Since 1996 he has been involved in tunnel safety. In that domain he has developed a new model for the evaluation of accidental risks in underground networks, named NewVendis which is today a key model of the research work program of the on-going UPTUN project within the 5th framework programme. He has led the ventilation measurement campaign during the legal on-site enquiry of the Mont Blanc tunnel catastrophe and has participated in the fire scenario reconstitution. He recently participated in the review of the Global Safety Case of the Channel Tunnel as safety expert of the French delegation. Since 2001 he has been the Program Manager for ‘Tunnels Safety and Transportation of Dangerous Goods’. In the field of Dangerous Goods (DGs) he has followed up the work initiated by INERIS for the road transport of DGs (development of the OECD/PIARC QRAM) by managing new developments in order to realise Comparative and Quantified Risk Assessment for Rail, Road and Multimodal transport of DGs. In that domain he is also involved in safety issues related to the nodal infrastructure of the transport chain. He is a Member of the Working Groups of the Committee for the Safety Assessment of
Road Tunnels. In that WG he contributes to the evolution of regulation and to the production of guidance for its application.

JAIME SANTOS-REYES, Research Associate, Heriot-Watt University, Edinburgh, UK.

Jaime Santos-Reyes’ main research interest is safety management systems. He obtained a PhD from Heriot-Watt in 2001 for his thesis *The Development of a Fire Safety Management System (FSMS)*. Since then he has used the systemic safety management system model that he developed to look at safety management on offshore installations, on the UK railway network and in tunnels. He is currently using the model to analyse a number of accidents that have occurred in other industries. He has a degree in Mechanical Engineering from the Instituto Politecnico Nacional, Mexico and an MSc in Thermal Power and Fluid Engineering from UMIST, UK. He has also spent some years working in the oil and gas industry.

JIM SHIELDS, FireSERT Centre, University of Ulster, UK.

Jim Shields is a founding member of the Fire Safety Engineering Research and Technology Centre (FireSERT) at the University of Ulster. He was the Director of FireSERT since its establishment until January 2004. He has over 100 journal publications as well as several books. He serves on many national and international committees and was a Member of the Fire Authority for Northern Ireland and was Chair of the Authority’s Safety Committee. He serves on the Northern Ireland Buildings Regulations Committee (NIBRAC) which advises the Department of Environment Finance and Personnel Office Estates and Building Standards Division on Building Regulation matters. He is a UK delegate to ISO TC92/SC4 and was liaison between ISO TC92/SC4 and C1B W14 Fire. He led UoE33 Built Environment through the 1992, 1996 and 2002 Research Assessment Exercise to great success. He is the founder and co-ordinator of the Fire Safety Engineering Networks (FERN) and Human Behaviour in Fire (HUBFIN) in the UK. He has served on the Council of the University. His contribution to Fire Safety Engineering was recognised by the Association of Building Engineers in 1995 when he was their recipient of the prestigious Fire Safety Award.

MARTIN SHIPP, Associate Director, FRS, and Head of FRS Centre for Fire Safety in Transport, Building Research Establishment, UK.

Martin Shipp joined FRS in 1974. He is responsible for fire investigation, fire safety management and projects related to all aspects of transport fire safety. Since 1988 he has headed the FRS team carrying out fire investigations, including Piper Alpha (1988), and Windsor Castle (1992). He is a Member of the Management Committee of the UK Forum of Arson Investigators and is a Guest Member of the European Network of Forensic Science Institutes Fire and Explosion Investigation Working Group. He was a Member of the Safety Authority investigation into the Channel Tunnel fire in 1996 and the Railtrack investigation into the Paddington Railway Fire in 1999. He assisted Bedfordshire Police with the investigation into the Yarl’s Wood Detention Centre Fire (2002).
Contents

Preface, Alan Beard and Richard Carvel iii
Biographies iv
Introduction: tunnel fire safety decision-making and knowledge, Alan Beard xvii

Part I. Real tunnel fires 1

1. A history of fire incidents in tunnels 3
   Richard Carvel and Guy Marlair
   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

2. Tunnel fire investigation I: The Channel Tunnel fire, 18 November 1996 42
   Martin Shipp
   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

3. Tunnel fire investigation II: The St Gotthard Tunnel fire, 24 October 2001 53
   Jean-Claude Martin, Olivier Delémont and Claude Calisti. Translated by R. Carvel
   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
12. CFD modelling of tunnel fires

Norman Rhodes

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

13. Control volume modelling of tunnel fires

David Charters

Introduction 284
Application of control volumes to tunnel fires 284
Application of control volume models to tunnel fire safety 290
Summary 297
References 297

14. Problems with using models for fire safety

Alan Beard

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

Part IV. Fire safety management and human factors

15. Human behaviour in tunnel fires

Jim Shields

Introduction 323
Some recent tunnel fires 323
Towards understanding human behaviour in tunnel fires 329
Responding to a developing emergency 338
## 16. Recommended behaviour for road tunnel users

*Michel Egger*

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction</td>
<td>343</td>
</tr>
<tr>
<td>Safety and risks in road traffic</td>
<td>344</td>
</tr>
<tr>
<td>Safety objectives in road tunnels</td>
<td>345</td>
</tr>
<tr>
<td>Road users as a factor influencing safety in road tunnels</td>
<td>347</td>
</tr>
<tr>
<td>Proposed measures for road users</td>
<td>349</td>
</tr>
<tr>
<td>Conclusions and outlook</td>
<td>353</td>
</tr>
<tr>
<td>References</td>
<td>353</td>
</tr>
</tbody>
</table>

## 17. Transport of hazardous goods

*Emmanuel Ruffin, Philippe Cassini and Hermann Knoflacher*

<table>
<thead>
<tr>
<th>Section I: Road tunnels</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>The situation concerning the road transport of hazardous goods in the European Union</td>
<td>354</td>
</tr>
<tr>
<td>Harmonised groupings of dangerous goods</td>
<td>355</td>
</tr>
<tr>
<td>Quantitative risk assessment model</td>
<td>366</td>
</tr>
<tr>
<td>Risk reduction measures for road tunnels</td>
<td>374</td>
</tr>
<tr>
<td>Member states' experiences of the QRAM</td>
<td>376</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Section II: Rail transport and road/rail intermodality</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>The situation concerning the rail transport of hazardous goods in the EU</td>
<td>381</td>
</tr>
<tr>
<td>The situation in the professional engineering world for rail transport</td>
<td>382</td>
</tr>
<tr>
<td>A new QRA model for rail</td>
<td>383</td>
</tr>
<tr>
<td>Conclusions</td>
<td>385</td>
</tr>
<tr>
<td>References</td>
<td>386</td>
</tr>
</tbody>
</table>

## 18. A systemic approach to tunnel fire safety management

*Jaime Santos-Reyes and Alan Beard*

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction</td>
<td>388</td>
</tr>
<tr>
<td>A Tunnel Fire Safety Management System model</td>
<td>389</td>
</tr>
<tr>
<td>Fire safety performance</td>
<td>399</td>
</tr>
<tr>
<td>The MRA, the acceptable range of fire risk and the viability</td>
<td>403</td>
</tr>
<tr>
<td>Conclusion</td>
<td>403</td>
</tr>
<tr>
<td>Appendix 18.1. The four organisational principles</td>
<td>404</td>
</tr>
<tr>
<td>Appendix 18.2. Control and communication paradigms</td>
<td>405</td>
</tr>
<tr>
<td>References</td>
<td>406</td>
</tr>
</tbody>
</table>

## 19. Road tunnel operation during a fire emergency

*John Gillard*

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>General introduction</td>
<td>408</td>
</tr>
<tr>
<td>The stakeholders in tunnel safety</td>
<td>409</td>
</tr>
<tr>
<td>The factors that influence tunnel operational safety</td>
<td>410</td>
</tr>
<tr>
<td>The nature of incidents</td>
<td>412</td>
</tr>
<tr>
<td>Liaison between tunnel operator and emergency services</td>
<td>414</td>
</tr>
<tr>
<td>Incident response</td>
<td>416</td>
</tr>
<tr>
<td>Decisions and actions</td>
<td>417</td>
</tr>
</tbody>
</table>
The general shift away from prescriptive to performance-based decision-making with regard to tunnel fire safety is a double-edged sword. In some ways it is a very desirable shift but in other ways it may backfire. Whatever else it implies, it means that there is a need to assess the risk in some way and this is good. Prescriptive regulations, including ‘best practice’ codes and guides, have played a vital role in society, and should continue to do so. The key objective of tunnel fire safety decision-making may be seen as to maintain risks within acceptable ranges. This would be with respect to: (1) fatality and injury, (2) property loss and (3) disruption of operation. However, with a purely prescriptive approach tunnel designers, operators and users are effectively unaware of what the risks are with regard to the three categories above. Historical statistics give us some idea of the risk implicit in a particular system; however, there is a crucial problem with simply looking at statistics and that is this: the system changes over time. Simply considering historical statistics with regard to a particular tunnel over a long period, say 20 years, may be very misleading because it is certain that the system as it exists at one point will be different to the system which exists 20 years later – or even five or ten years later. To consider just one factor alone, increasing traffic volume probably means that the systems associated with most road tunnels have changed dramatically in recent years. While a prescriptive approach would not recognise this (at least explicitly), it would be recognised in a ‘risk-based’ approach; or at least it should be. That is, a risk-based approach has the potential to be very valuable in helping us cope with decision-making in an increasingly complex and ever-changing world.

However, the prescriptive approach should continue to be very valuable into the indefinite future, since it represents a great fund of knowledge and experience gained over many years. Prescriptive features have a very important part to play along with a risk-based approach. The question is not so much ‘how can a risk-based approach replace a prescriptive approach?’ so much as ‘how can prescriptive elements play a valuable role as part of a risk-based approach?’ Both prescriptive and risk-based
approaches have their positive and negative aspects: while prescriptive codes do not allow us to understand the risk explicitly, they often represent a rich seam of knowledge and experience grounded in the real world. Conversely, while a risk-based approach does, in principle, allow us to appreciate what the risk is, there are considerable problems associated with assessing risk and being able to use that modelling as part of tunnel fire safety decision-making in an effective and acceptable way.

The issue relates to knowing what methodology to adopt when applying a risk-based approach. Methodologies range from a very ‘hard’ methodology, in which there is overwhelming agreement among the ‘actors’ or ‘participants’ as to what the problem is and what is desirable, through to ‘soft systems’ methodologies. In a purely ‘hard’ methodology there is considerable knowledge and understanding of the system, very little uncertainty and no iteration in the decision-making process. The method proceeds from ‘problem’ to ‘solution’ in a mechanical orderly manner; see, for example, Reference 1. While such an approach may be suitable for some situations, e.g. putting in a simple telephone system, it is not suitable for tunnel fire safety. At the other end of the spectrum are the ‘soft systems’ methodologies, for example the one by Checkland.2 The essential features of a soft systems approach are the existence of different points of view among the people involved and affected and lack of reliable knowledge about the system. There will usually be considerable uncertainty and may be differences of opinion as to what the ‘problem’ actually is. Classic soft systems problems are those associated with, say, healthcare.

Between the hard and soft ends of the spectrum of methodologies are the intermediate methodologies. It is likely that an intermediate methodology would be appropriate for decision-making with respect to tunnel fire safety. A methodology which is intermediate but lies towards the hard end of the spectrum is the one outlined by Charters3 in Figure 0.1.

While this contains an iteration loop (one characteristic of an intermediate methodology), the degree to which it is hard or not depends upon how much time and effort is put into each of the stages, for example the stage aimed at deciding whether or not the risk implicit in an option is acceptable. Another intermediate methodology is that constructed by the current author,4,5 an amended version of which is shown in Figure 0.2. This spends much more time in the earlier stages and includes an iteration loop after every stage. There is also an emphasis on learning from ‘near misses’. Near misses represent a very great source of information and knowledge about the behaviour of real-world systems and we should tap this source much more than we do at the present time. While this methodology is intermediate it leans more towards the softer end of the spectrum than does the methodology described by Charters.

Having decided on an overall methodology, with a risk-based approach it becomes necessary to construct models in relation to tunnel fires and the models constructed become ever more complex. There are fundamental problems associated with constructing and using models in a reliable and acceptable way. Every quantitative model makes conceptual assumptions and these may be inadequate. There may be, for example, possible real-world sequences which we simply do not know about and which, therefore, have not been considered in an analysis at all; this would be in addition to possibly unrealistic assumptions about sequences which have been included in an analysis. For example, a sequence involving a heavy goods vehicle (HGV) on fire may be included in an analysis but the assumptions about fire development and
spread may be unrealistic. Considerations of this kind have been discussed further in reference. In addition to possible uncertainty or ignorance about conceptual assumptions there is the problem of uncertainty about numerical assumptions. These difficulties mean that, even if a model has the potential to be valuable, acceptable use of a model is generally very problematic and requires a knowledgeable user employing an acceptable approach. As a general rule the conditions do not yet exist for reliable and acceptable use of complex computer-based models as part of tunnel fire safety decision-making. These conditions need to be created.

Some basic issues, in no particular order of importance, which exist in relation to tunnel fire safety and which we need to be able to cope with are given below; there is no doubt that there are many others.

- Fire risk in tunnels is a result of the working of a system involving design, operation, emergency response and tunnel use. That is, fire risk is a systemic product. Further, this ‘tunnel system’ involves both ‘designed parts’ and ‘non-designed parts’, for example traffic volume or individual behaviour of users. The designed parts need to take account of the non-designed parts as much as possible.
- Tunnels are becoming ever larger and more complex; we need to be able to deal with this.
- The system changes. A tunnel system which exists at the time of opening will be different to the tunnel system which exists a few years later.
- What are to be regarded as acceptable ranges for fire risks with regard to: (1) fatality/injury, (2) property loss and (3) disruption of operation? As a corollary: what are to be regarded as acceptable ranges for an upgraded existing tunnel as opposed to a new tunnel?
- What is to be an acceptable methodology for tunnel fire safety decision-making?
The part played by models in tunnel fire safety decision-making. Models, especially computer-based models, have the potential to play a very valuable role. However, an acceptable context within which models may be employed in a reliable and acceptable way needs to be created. This implies: (1) independent assessment of models, their limitations and conditions of applicability; (2) acceptable ‘methodologies of use’ for models given cases; (3) knowledgeable users who are familiar both with the

Figure 0.2. Intermediate methodology B
model and fire science. Models should only ever be used in a supportive role, in the context of other fire knowledge and experience.

- An overarching probabilistic framework needs to be created, within which both probabilistic and deterministic models may play a part. A synthesis of deterministic and probabilistic modelling needs to be brought about.
- Experimental tests: we need large and full-scale tests as well as small-scale tests.
- Also, we need replication of experimental tests, because of the variability of experimental results for ostensibly ‘identical’ tests.
- Operator response: (1) to what extent is automation feasible or desirable? (2) to what extent can decision-making during an emergency be simplified and yet still be able to cope effectively with different emergency situations, in increasingly complex tunnel systems?
- Tunnel fire dynamics: we know more than we did but we need to know much more.
- Fire suppression: what kinds of systems are appropriate?
- How is real human behaviour to be taken account of in tunnel fire emergencies? At present we know very little.

Whatever else follows from considering the above issues, one thing is certain: a sound understanding of tunnel fire science and engineering is needed. Further, this needs to be seen in its widest sense to include, for example, human behaviour and what risk is to be regarded as socially acceptable. While a significant amount of tunnel fire research has been carried out in recent years, much remains to be done. Moreover, as systems change then there will be a continual need for fire research to understand the nature of fire risk in tunnels and be able to control it in an acceptable way. Needed research is implied by the issues raised above. More specifically, to pinpoint a very few, some key research questions which we need answers to are:

(a) What are effective ways of preventing fires occurring in tunnels?
(b) What are the factors affecting tunnel fire size and spread?
(c) What are the characteristics of different tunnel fire suppression systems?
(d) How do human beings behave in tunnel fire emergencies – both users and tunnel staff/fire brigade personnel?
(e) What are effective evacuation systems?
(f) To what extent can emergency response be ‘automated’?
(g) How do we deal with uncertainty in models which are used as part of fire safety decision-making?

Other issues and needed research areas are implied in the chapters of this Handbook and especially in the chapter on ‘Tunnel fire safety and the law’ by Arnold Dix (Chapter 20). Addressing the research required as a result of considering the above issues and key research questions will require willingness by researchers to become engaged in such areas and also funding. International collaboration in research has played an important role in the past and it may be expected to continue to do so. There needs to be a strategy for tunnel fire research, involving both international collaboration and effort by individual countries. Further, there needs to be an openness about research results. It is not acceptable for results to be kept secret. However it is done, these issues and implied research areas need to be addressed for the benefit of all countries and their citizens.
References

7. Tunnel ventilation – state of the art

Art Bendelius, Parsons Brinckerhoff, USA

Introduction

Webster’s dictionary defines ventilation simply as ‘circulation of air’. Ventilation does not necessarily mean the use of mechanical devices such as fans being employed; the non-fan or natural ventilation is still considered to be ventilation. From that simple definition of ventilation we move forward to the ventilation of tunnels. The use of tunnels dates back to early civilisations and so too does ventilation in the form of natural ventilation. However, the ventilation of tunnels has taken on greater significance within the past century, due to the invention and application of steam engines and internal combustion engines which are prevalent as motive power in the transport industry. This all became evident as increasing quantities of combustion products and heat would become more troublesome to the travelling public.

Exposure to the products of combustion generated by vehicles travelling through a tunnel can cause discomfort and illness to vehicle occupants. Ventilation became the solution by providing a means to dilute the contaminants and to provide a respirable environment for the vehicle occupants. Visibility within the tunnel will also be aided by the dilution effect of the ventilation air.

In the past quarter century, great concern has arisen regarding the fire life safety of the vehicle occupants in all transport tunnels. Much effort has been made to improve the fire life safety within tunnels, thus focusing more attention on the emergency ventilation systems installed within tunnels.

The use of the term ‘tunnel’ in this chapter refers to all transportation-related tunnels including road tunnels, transit (metro or subway) tunnels and railway tunnels.

Road tunnels, from a ventilation viewpoint, are defined as any enclosure through which road vehicles travel. This definition includes not only those facilities that are built as tunnels, but those that result from other construction such as development of air rights over roads. All road tunnels require ventilation, which can be provided by natural means, traffic-induced piston effects and mechanical ventilation equipment. Ventilation is required to limit the concentration of obnoxious or dangerous contaminants to acceptable levels during normal operation and to remove and control smoke and hot gases during fire-based emergencies. The ventilation system selected must meet
the specified criteria for both normal and emergency operations and should be the most economical solution considering both construction and operating costs.

The portions of transit (metro) systems located below the surface in underground structures most likely will require control of the environment. In transit (metro) systems, there are two types of tunnel: the standard underground tunnel, which is usually located between stations and normally constructed beneath surface developments with numerous ventilation shafts and exits communicating with the surface; and the long tunnel, usually crossing under a body of water, or through a mountain. The ventilation concepts for these two types will be different, since in the long tunnel there is usually limited ability to locate a shaft at any intermediate point, as can be accomplished in the standard underground tunnel. The characteristics for a long transit tunnel will be similar to the ventilation requirements for a railway tunnel.

Ventilation is required in many railway tunnels to remove the heat generated by the locomotive units and to change the air within the tunnel, thus flushing the tunnel of pollutants. Ventilation can take the form of natural, piston effect or mechanical ventilation. While the train is in the tunnel, the heat is removed by an adequate flow of air with respect to the train, whereas the air contaminants are best removed when there is a positive airflow out of the tunnel portal.

**The early ventilation concepts**

The earliest evidence of serious consideration of ventilation appeared in the transit or metro tunnels where the ventilation of transit (metro) tunnels was accomplished by utilising the piston effect generated by the moving trains and by installing large grating-covered openings in the surface, sometimes called ‘blow-holes’, thus permitting a continuous exchange of air (when trains were running) with the outside and subsequently lowering the tunnel air temperature. However, in the early part of the twentieth century, when the air temperatures in the tunnels began to rise in both London and New York, mechanical means of ventilation (fans) began to be employed.

One of the first formal ventilation systems in a road tunnel was in the Holland Tunnel (New York) in the 1920s. A significant amount of testing was performed in the United States by the US Bureau of Mines\(^1\) prior to the design and construction of the Holland Tunnel which opened to traffic in 1927. The use of mechanical ventilation in road tunnels coincided with the growing concern for the impact of the exhaust gases from internal combustion engine propelled vehicles in road tunnels.

**Types of ventilation system**

There are two basic types of ventilation airflow systems applied in transport tunnels: longitudinal and transverse.

**Longitudinal.** The airflow is longitudinal through the tunnel and essentially moves the pollutants and/or heated gases along with the incoming fresh air and provides fresh air at the beginning of the tunnel or tunnel section and discharges heated or polluted air at the tunnel portal or at the end of the tunnel section (see Figure 7.1). Longitudinal ventilation can be configured either portal to portal, portal to shaft or shaft to shaft as shown in Figure 7.1. The air entering the tunnel is at ambient conditions and is impacted by the pollution contaminants and the heated gases from
the vehicles moving through the tunnel, as clearly seen in Figure 7.2. It is longitudinal airflow which is applied most often in transit (metro) and railway tunnels.

**Transverse.** Transverse flow is created by the uniform distribution of fresh air and/or uniform collection of vitiated air along the length of the tunnel. This airflow format is used mostly in road tunnels although it is occasionally applied for unique circumstances in transit tunnels. The uniform distribution and collection of air throughout the length of a tunnel will provide a consistent level of temperature and pollutants throughout the tunnel. The transverse ventilation system can be configured as fully transverse or semi-transverse.

**Mechanical versus natural ventilation systems**

An evaluation of the natural ventilation effects in a tunnel must determine whether a sufficient amount of the heat and/or pollutants emitted from the vehicles is being
Index

before 1940 fire incidents 36–7
1940–60s fire incidents 34–6
1970s fire incidents 30–4
1980s fire incidents 24–30
1990s fire incidents 17–24
2000 to present incidents 10–17
615b test 278–82

‘A’ series FIRE-SPRINT models 160–2
acceptable ranges, risk xix
access see means of access
accidents
  computer-based program 475
  rules 347–9
  scenarios 369–74
ACTEURS project 339
active fire protection 87–8, 113, 119–22, 416–17
activity attachment 336
additives, concrete 118
age factors 334
agencies 442
air ducts 439
air flow velocities 156, 241–5
alarm systems
  architecture 98–9
  assessment 103–5
  emergency procedures 468–9, 475–6
  state-of-the-art 103–5
  systems architecture 107–8
  video-image processing 107–8
alertness 100–5, 336–7
American Society of Heating, Refrigerating and
  Air-conditioning Engineers (ASHRAE) 154–5
ammonia release 368
analyses, see also sampling and analyses
annual emergency procedure exercises 479–80
architecture see systems architecture
ASET see available safe egress time
Ashby’s law 395, 404
ASHRAE see American Society of Heating,
  Refrigerating and Air-conditioning Engineers
assessment, alarm systems 103–5
Australia 219, 226, 427
Austria
  Kaisermühlen Tunnel 369
  Kaprun (Kilstein) tunnel fire 6–7, 326–7, 328, 331
  QRAM experiences 376–7
  Tauern Tunnel fire 326, 328
available safe egress time (ASET) 333, 334
avoidance measures 89–91
axial flow fans 135
Azerbaijan 324–5, 328, 498
Barezgi Tunnel 213–14
basic issues xix–xxi, 184–6
Bayes’ theorem 187–8
beam detectors 95, 96
behaviour
  concrete 111–13
  road tunnel users 343–53
  when driving 347–9
see also human behaviour
Beneluex Tunnel (2nd) fire tests 209–10, 254
BHRG/BHRA see British Hydrodynamics Research
  Group
bi-directional communication paradigms 406
boiling liquid expanding vapour explosion (BLEVE)
  357, 358, 371
bored tube tunnels 111
bottom line 472, 473
boundary conditions 272–3, 278
breathing apparatus 484–8, 495, 499–500
British Hydrodynamics Research Group (BHRG was
  BHRA) 137
BRONZE incident level 421
burning process 251, 258–9
burning rate see fire heat release rate
Byfjord Tunnel 217
cables 101, 207–8
Caldecott Tunnel 5, 173–4, 324, 328
CALs see current achievement levels
car fires 195
carbon monoxide/dioxide ratio techniques 252–4
case studies 189–95, 275–82, 308–13
casualties 295
causation, prevention and protection 83
  cause of fire 64–71
CCTV image processing systems 105–8
ceilings 55, 58, 255–6
centrifugal fans 136
CEs see crucial events
CFD testing 223–4
CFX software 176
Channel Tunnel 7
  Safety Authority 44–6, 48, 49, 51–2
  supplementary ventilation system 151, 152
  ventilation systems 145, 151, 152, 159–60
Channel Tunnel fire 325, 328, 331
  chronology 45
CTSA investigations 44–6, 48, 49
damage 46–7
discussion 50–1
findings 48–9
fire spread 260, 261
HGV shuttles 43
human behaviour 325, 328, 331
incident 44, 45, 48–9
investigation 42–52
issues 49–50
lessons 49–50
safety experiments 224–5
safety systems 43–4
suppression tests 208
tunnel system 42–3
bottom line 472, 473
common features 453, 456
computer-based accident program 475
contingency planning 441–5, 457–65
cooperative exercises 479
current practice 437–80
education 468–73, 478
emergency services 476–8
engineering services 439–40
equipment 467–8
evacuation 467
feedback 444–5
fixed installations 439–40, 467
future ideas 437–80
Great Belt Tunnel example 473–80
incident management 446–7
independent exercises 478–9
initial response 468–9
key agencies 442
key factors 467, 469–70
materials 467–8
objectives 465–6
organisation 468
overview 464–5
personnel 468
phases 467, 469–70
planning 441–5, 457–61, 466
precautions 467
rail tunnels 451–80
rapid response teams 446
reconnaissance visits 443–4
response 441, 468–9
response schematics 470, 472
response team location 445–6
road tunnels 437–50
safety management 437–41
self-rescue 468–9, 476
service intervention 469–70
simplified plans 460–1
standard operational procedures 451–7
testing 444, 461–2
time 471–3
traffic management 440–1
training 462–4, 468–73, 478
validation 461–2
where, when and why 456–7
see also incident response
emergency services 414–15, 476–8
engineering 424–5, 439–40
enhanced user interface 379
environmental damage 369
equipment
emergency procedures 467–8
provision 445
standards 410
surveillance 490–1
error sources, theoretical models 308–9
EUREKA Firetun projects 157, 158, 176, 204–6, 256–7
European Union (EU) 354–5, 381–2
Eurotunnel see Channel Tunnel
evacuation 491–3
egress capability profiles 323
emergency procedures 476
modelling 315
safety tunnels 346
space 482
evaluation units 103
event trees 85, 86, 90, 371
evidence 427–8
exhaust semi-transverse ventilation systems 133–4
exits 348, 349
experimental testing 201–30
basic issues xxi
Japan 147
non-tunnel 224–6
safety places 219–20
small scale 218–21
sprinkler evaluation 212–13
theoretical results comparisons 311–13
water suppression systems 121–2
explosions 54, 55, 71, 225–6, 357
see also boiling liquid expanding vapour explosion
externally committed systems (ECSs) 397, 398
extinguishing fires 486–7, 501–2
F–N curves 296, 368
fail-safe systems 97–8
false alarm safe systems 97–8
false inferences 305–6
fans 135–6, 150–1
FASIT (Fire growth And Smoke movement In Tunnels) model 169–70
FCEs see fundamental crucial events
FDS V2.0 model 175–6
feedback 405, 444–5
FFF Tunnel 216
fibre-optic cables 102
fibre-reinforced composites 118
fibreglass conductors 102–3
fidelity lack 309–10
Finland 121–2
fire characteristics 157–65, 184–98
fire detection 93–109
beam smoke detectors 95, 96
detector types 95
future trends 105–8
heat 96–7
line-type heat detectors 101–3
operational performance requirements 99–100
principles 94, 97–8
problems 93–8
smoke 94–5, 96
see also heat detectors; smoke detectors
fire dynamics 199–320
compartment fires 232–7
fire development 93–4, 233–5
fire spread 259–62
flame length 254–8
flashover 235–7
fuel control 238–9
HRR determination 252–4
longitudinal flow 245–52
nomenclature 262–3
open fires 231–2
smoke stratification 241–5
ventilation control 238–9
fire experiments 201–15
fire gases 493–4, 497–9
fire growth 189–91, 290–1
fire loads 345
fire modelling 273–4, 277–8, 299–300, 316
see also computational fluid dynamics modelling
fire movement 165–76
fire propagation 62–3
fire protection
alternative suppression systems 122–3
composite layers 118
concepts 87–8
concrete tunnels 110–26
fibre-reinforced composites 118
Finland 121–2
fire protection (continued)

inadequate 111
Netherlands 114
structural integrity 110–26
see also active fire protection; passive fire protection

fire risk indices 401

fire safety
acceptable methodologies 313–14
application mistakes 311
case study 308–13
Channel Tunnel 224–5
decision making 306–8
deterministic models 303–4, 305
documentation inadequacy 311
evacuation modelling 315
experiments 224–5
false inferences 305–6
fire model term 299–300
fire scenario selection 332
knowledgeable users 314–15
management 86–7, 321–43
see also Tunnel Fire Safety Management System
model
methodology of use 313–14
models 299–319
performance 399–403
planning 401
probabilistic models 303, 304–5
qualitative results 315
quantitative results 315
risk levels 400
software mistakes 310
specific model potential 313
statistics problems 306–5
systemic approach 388–407
theoretical models 302–6, 308–9, 311–13
validation 307–8
value potential 306–7
fire scenarios 294–5, 332
fire science 184–6
fire sequence 91
Fire and Smoke Control in Road Tunnels report 119–21
fire sources 186–7
fire spread 72–3, 159–62, 259–62
fire suppression tests 208, 209, 212–13
fire tenability 292–5
fire types 187
fire-fighters 485, 488, 494–5
FIRE-SPRINT (fire spread in tunnels) models 160–2, 260–1
FirePASS system (Fire Prevention And Suppression System) 122–3
Firetun projects see EUREKA . . .
fixed installations 439–40, 467
flames 95–6, 185, 254–8
flaming fire tests 106–7
flashover 157–62, 235–7
flow rate/time graphs 279
FLOW3D simulations 174–5
Fluid Dynamics Simulator (FDS) software 172
foam–water sprinkler systems 121
forced air velocity group 242–3
forced ventilation 185, 190–5
France

corporate liability 425–6
Grand Mare Tunnel 216–17
INERIS 206, 219–20
OECD/PIARC QRAM use 377–81
regulation framework 377–81
see also Channel Tunnel; Mont Blanc tunnel
Frejus Tunnel 216

Froude scaling 164, 218, 222
fuel-controlled fires 185, 234, 237–41
fuel-lean fires 185, 234, 237–41
fuel-rich fires see ventilation-controlled fires
fuel oil 69–70
fuels
combustion products 248–9
fire causes 64–5
ignition 65–6
mass optical density 251
nature of 64–5
origins 68–9
fundamental crucial events (FCEs) 84–6
future
emergency procedures 437–80
fire detection 105–8
multimodal platform models 383–5
rail tunnels 451–80
ventilation 140
gas
concentrations 248–50
escapes 421
flow 218–19
temperature 245–8
geographical information system (GIS) 378–81
Germany 114, 115, 426
GIS (geographical information system) 378–81
Glasgow Tunnel fire experiments 202–3
GOLD incident level 421, 446
Grand Mare Tunnel, Rouen 216–17
Great Belt Tunnel, Denmark 464, 473–80
groupings
dangerous goods 355–66
principles 356–7
proposed system 357–66
QRAM 366
system description 358–9
guidelines, ventilation 138–9, 140

Hammerfest Tunnel 205–6
handbooks, ventilation 138–9
hazard development 333
hazardous goods transport 354–87
European Union 354–5, 381–2
rail transport 381–6
road tunnels 354–81
see also dangerous goods
hazardous spillages 420
hazards, risk comparison 81–2
Health and Safety Laboratory (HSL) 174–5
heat
control within 2 minutes 99
detectors 96–7, 102–3
development 93–4
movement 207
rated cables 101
see also temperature
heat fractional effective dose see fire tenability
heat release rate (HRR)
compartment fires 232
determination 252–4
fires 164, 185–98, 345
non-dimensional flame lengths 257–8
ventilation influence 254
heat release variation 158–9
heat release/time graphs 278–9
heat transfer 185, 186, 287–9
HGVs (heavy goods vehicles) 3, 6
EUREKA 499 fire tests 256–7
fire event trees, QRAM 371
fire growth 189–91, 196
power supplies 70
shuttles 43
trailers 62, 63
high air velocity group 242–3
history 3–41
before 1940 fire incidents 36–7
1940–60s fire incidents 34–6
1970s fire incidents 30–4
1980s fire incidents 24–30
1990s fire incidents 17–24
2000 to present 17
experimental tunnel fires 201–30
incidents list 9–37
HRR see heat release rate
HSE tunnel, UK 220, 223
human behaviour
age factors 334–5
alertness 336–7
available safe egress time 333, 334
Baku rail/metro fire 324–5, 328
Caldecott Tunnel 324, 328
Channel Tunnel fire 325, 328, 331
commitment 336
familiarity 335
fires 332–4
gender 334
hazard development 333
major tunnel fires 327–9
Mont Blanc tunnel fire 325, 328
object/activity attachment 336
occupant characteristics 334, 336
panic concept 337–8
physical/sensory capabilities 335
pre-evacuation activity times 333
recent developments 338–9
required safe egress time 333
responsibility/role 336
social affiliation 336
Tauern Tunnel fire 326, 328
tunnel fires 323–42
understanding 329–38
human factors 321–434
Hwang et al. model 168, 169
hybrid models 168
ICSs see internally committed systems
ignition 69–72, 82–3
image processing systems 105–8
immersed tube tunnels 111, 113
incident response 408–21
actions 417–21
concepts 416–17
decisions 417–21
passive stage 416
stages 416–17
standards 411
see also emergency procedures
incidents
Channel Tunnel findings 48–9
chronology 45, 60, 61
legal investigations 422–8
list 9–37
management 446–9
nature of 412–14
see also history
indicators, QRAM 368
individual risk, QRAM 369
INERIS, France 206, 219–20, 383–5
information campaigns 349–50
lack 489–90
systems 353
initial response procedures 468–9
installation-type longitudinal ventilation systems 131
injuries 420
installation commissioning 213–15
integration, systems 447–9
intermediate methodologies xviii–xix
internally committed systems (ICSs) 397, 398–9
international incidents 8–9
investigations 42–76
Channel Tunnel fire 42–52
issues to beware of 432–3
Mont Blanc Tunnel fire 208–9
St Gotthard Tunnel fire 53–76
see also legal investigations
Italy 4, 325, 328, 426
Japan
experiments 147
fire suppression systems testing 212–13
Nihonzaka Tunnel 5
PWRI Tunnel fire experiments 204
small scale fire experiments 219
Toumei-Meishin expressway tunnel 210
JASMINe (smoke movement in enclosures) code 173–4
jet fans 131–2, 150, 276, 277
Kaisermühlen Tunnel, Vienna 369
Kaprun (Kilzstein) tunnel fire, Austria 6, 326–7, 328, 331, 493, 494
King’s Cross fire, UK 491
knowledge xvii–xxii
knowledgeable users 314–15
laboratories 76, 221–4
large eddy simulations (LES) 172, 176
large pool fires 194, 196
law, safety 422–34
layered structure, TFSMS model 392
legal investigations
decisions 428–33
economic considerations 430
evidence 427–8
incidents 422–8
issues to beware of 432–3
past decisions 428–33
risk analysis 430–1
legal powers, incidents 423
LES see large eddy simulations
Linden model see Daish and Linden model
line-type heat fire detectors 101–5
lining systems 115–18
locations, response teams 445–6
long-term objective index (LTOI) 402
longitudinal flow
average flow conditions 245–52
carbon monoxide/dioxide ratio techniques 252–4
gas concentrations 248–50
gas temperature 245–8
velocity 245–8
visibility 250–2
longitudinal grids 276, 277
longitudinal ventilation systems 128–9
design for safety 148
flame length 256–8
large fires 258–9
mechanical 131–2
Memorial Tunnel Program 207
Mont Blanc road tunnel 156
longitudinal ventilation systems (continued)
  natural 188–97
  plumes 288
  typical arrangements 150
  zones 258–9
lost time injuries (LTI) 398
low air velocity group 241–2
LTOI see long-term objective index

Madrid Metro tests 209
MAGs see model assessment groups
maintenance standards 410–11
major extra investment level (MAJEIL) 400–1
major incidents
  avoidance measures 90–1
  definition 446
  human behaviour 327–9
  levels 421
  responses 419–20
  ventilation influence 159–62
  see also incident response management
  and design integration 447–9
  human factors 321–434
  see also traffic management
map, Austria 376
MRA see maximum risk acceptable
mass flow 286
mass and heat transfer sub-models 287–9
mass optical density 251
maximum risk acceptable (MRA) 403
means of access/escape 439, 496–7
measurement systems 399
mechanical ventilation systems 131–4, 147–51
medium pool fires 192–4
Memorial Tunnel experiments
  615b test 278–82
  boundary conditions 278
  case studies 275–82
  CFD modelling 275–82
  fire modelling 277–8
  flow rate/time graphs 279
  heat release/time graphs 278–9
  modelling approach 276–7
  physical situation 276
  steady-state model tests 278
  transient simulation 278–82
  upstream fire temperatures 280–1
  volumetric flow 278
Memorial Tunnel Fire Ventilation Test Program
  (MTFVTP) 121, 206–7
  design for safety tests 155–7
  fire fanning tests 150–1
  mechanical ventilation systems 132, 134
  methodologies xviii–xx, 313–14, 367
  metro systems 455–6
  MFIRE models 166
  minor extra investment level (MINEIL) 400–1
  mistakes, software 310
  model assessment groups (MAGs) 307
  models 165–76
  decision-making xix–xxi
  phenomenological 167–70
  potential 313
  reality 309–10
  results variability 305
  see also CFD modelling; quantitative risk
  assessment models; theoretical models; Tunnel
  Fire Safety Management System model;
turbulence models
  moderate air velocity group 242
Monaco Branch Tunnel 216
monitoring equipment 490–1
Mont Blanc road tunnel 4, 148–50, 156–7, 343
  human behaviour 325, 328
  investigations 208–9
  refurbishment 116
Mornay Tunnel 7
  motors 136
MTFVTP see Memorial Tunnel Fire Ventilation Test Program
  multimodal platform model future 383–5
National Fire Protection Association 121, 157
National Institute of Standards and Technology (NIST) 172
NATM see New Austrian Tunnel Method
natural ventilation 130–1
  flame heat transfer to burning object 185
  heat release rate 188–97
  longitudinal 188–97
  operating modes during fire 146–7
  plumes 288
  tunnel fires 188–97
Netherlands 114, 159, 209–10, 254, 426
  network ventilation modelling 166–7
  New Austrian Tunnel Method (NATM) 111
  new technologies 105–8
  New Zealand 207–8
Nihonzaka Tunnel, Japan 5
NIST see National Institute of Standards and Technology
Nogent-Sur-Marne covered trench 215–16
  non-dimensional numbers 164, 218–19, 222, 257–8
  non-tunnel fire experiments 224–6
  Norway 211–12, 312, 426
  notation, CFD modelling 282
  numerical solution procedures 309–10
  objectives 345–7, 465–6
  occupants 330, 334, 336
OECD see Organisation for Economic Cooperation and
  Development
Ofenegg Tunnel 201–2
OFROU Task Force 226
older tunnels 144–5
  one tunnel systems 453–4, 502–3
  open fire dynamics 231–2
  operational procedures see emergency procedures
  operational safety factors 410–12
  operations systems 146–57, 408–21
  opinion evidence 428
  organic fire protection coatings 119
  Organisation for Economic Cooperation and
  Development (OECD) 344, 351, 377–81
  organisational principles 404–5
  over-ventilated fires see fuel-controlled fires
  overtaking, driving 352
  overview difficulties 489–90
  oxygen consumption 252
  oxygen-rich fires 185, 234, 237–41
  oxygen-starved fires see ventilation-controlled fires
  panelling systems 117–18
  panic concept 337–8
  Paris Metro experiments 222
  passive fire protection 87–8, 113–19
  passive stages 416
  past decisions, legal investigations 428–33
  PEATS see pre-evacuation activity times
  people mobility 323
  performance, fire safety 399–403
personnel, emergency procedures 468
phases, emergency procedures 467, 469–70
phenomenological models 167–70
photographic evidence 66
physical capabilities, humans 335
physical phenomena, CFD modelling 271
PIARC (World Road Association) 119–21, 139, 351
fire control objectives 154
publications 154
recommendations 119–21, 150
smoke control objectives 154
piston relief ducts (PRDs) 151
planning
avoidance measures 89–91
emergency procedures 441–5, 457–60, 466
fire safety 401
questions 458–60
simplified plans 460–1
traffic management 418
see also contingency planning
plumes 243, 288
policy implementation 390
polystyrene packaging risk example 80
pool fire tests 206, 219
positive smoke control 148
post-flashover stage 233, 235, 236
power supplies, HGVs 70
PRDs see piston relief ducts
pre-evacuation activity times (PEATS) 333
pre-flashover stage 233
prefabricated structural lining elements 118
prescriptive codes 89
prevention and protection 77–198
avoidance measures 89–91
causation 83
concepts 82–3, 87
constitutive crucial events 85
text 83
crucial events 82–3
event trees 85, 86
fire safety management 86–7
fire sequence 91
fundamental crucial events 84–6
general concepts 79–92
summary 88–9
tunnel fires 83–6
principles see first principles
probabilistic models 303, 304–5
problems
fire safety models 299–319
rescue operations 489–503
professionals 353, 423–5, 429–30
Promatect lining systems 117
propane burning example 238
protection see prevention and protection
publications see prevention and protection
PWRI Tunnel fire experiments 204
quantitative results 315
quantitative results 315
quantitative risk assessment (QRA) 431
quantitative risk assessment (QRA) rail model 383–5
quantitative risk assessment (QRA) road model (QRAM) 355–81
accident scenarios 369–70
Austrian experience 376–7
BLEVEs 371–3
characteristics 366–74
Decision Support Model consistency 359
enhanced user interface 379
French experience 377–81
GIS interface 378–81
groupings, representative goods 366
HGV fire event trees 371
indicators 368
individual risk 369
methodology 367
new structure 378
problem description 367
purpose 367
representative goods, groupings 366
societal risk 368
quantitative risk comparisons 385
questions
rescue operations 483, 484
which need answers xxi
R&D, safety 393
RABT (Richtlinien für die Ausstattung und den Betrieb von Straßentunneln) curves 115
radiation models 172–3, 274
radio messages 347–8
rail carriage tests 226
rail transport 381–6
rail tunnels 6–7, 90, 451–80
rapid response teams 446
real tunnel fires 1–76
reality, models 300–3, 309
reconnaissance visits 443–4
reconnaissance visits 443–4
recursive structure, TFSMS model 392, 394
reduced-scale fire tests 220
refractory materials 116
refurbishment, Mont Blanc Tunnel 116
regulations
dangerous goods transport 351
French framework 377–81
objectives 355–6
rail transport 382–3
Swedish breathing apparatus 495
relative autonomy 394
relative long/medium-term objectives index 402
representative goods 366
required safe egress time (RSET) 333
rescue operations 481–504
exercise site 485–6
extinguishing extensive fires 486–7
fire gases 493–4
information lack 489–90
large numbers of people 491–3
problems/solutions 489–503
in progress 482–4
questions 483, 484
reference assumptions 481–2
situation at start 502
training 493
ventilation assistance 502–3
response
developing emergencies 338
team location 445–6
two tunnel tubes 477–8
Rhodes, N. 170–3
Rijkwaterstaat (RWS) curves 144
risk
acceptable ranges xix
approach methodologies xviii–xx
F–N curves 296
fire fighters 494–5
fire spread between vehicles 259–62
hazards comparison 81–2
indices 401
informed methods 89–90
legal investigations 430–1
task Group 157
Tauern Tunnel fire 326, 328
Ted Williams Tunnel fire 327
temperature
fire spread 259–60
sensors 102
upstream 280–1
see also heat
terrorism 421
test programs, MTFVTP 121

St Gotthard Tunnel fire (Switzerland) 53–76, 327, 343
burning liquid 64
cause 64–71
combustion traces 63
cross-section 57
discussion 60, 67–8, 69, 74
explosion 54, 55, 71
fire fighting operations 58
fire origin 60–4
fire progression 62–3
fire propagation 71–3
fuel ignition 65–6
fuel origins 68–9
HGV's burning 64
ignition source 69–71
incident chronology 60, 61
incident summary 53–4
incident zone 55
ignition source 69–71
investigations 53–76
origins 62
photographic evidence 66
sampling and analyses 66–7
smoke damage 55, 56
smoke release 65
summary description 55–9
thermal degradation 73–4
topographic chart 55, 56
trailer ignition 72
tunnel ceiling 55, 58
tunnel lining 55, 57
vehicle damage 59, 62, 63
vehicle involvement 55, 56, 60–2
ventilation 55, 57
witness statements 64, 65–6
stoichiometric mixtures 237–41
stratified smoke 147
air velocity ranges 241–5
compartment fires 233
example 243–5
temperature regions 244
structural damage 369
structural integrity 110–26
structural lining elements 118
structural organisation 390–6
sub-models 287–9
Subway Environmental Design Handbook 154
Summit Tunnel fire 152
supplementary ventilation system (SVS) 151, 152
supply air semi-transverse ventilation systems 133
surveillance equipment 490–1
SVS see supplementary ventilation system
Sweden 220–1, 481–504
Switzerland 53–76, 213–14, 226, 343
Sydney Harbour Tunnel 134
systemic approaches 388–407
systemic products 79–81
systems
architecture 98–9, 107–8
performance 98–100

Task Group 157
Tauern Tunnel fire 326, 328
Ted Williams Tunnel fire 327
temperature
fire spread 259–60
sensors 102
upstream 280–1
see also heat
terrorism 421
test programs, MTFVTP 121

testing
costs 218
emergency procedures 461–2
operational tunnels 215–18
ventilation 139–40
theoretical models
error sources 308–9
experimental results comparisons 311–13
fire safety 302–6
results interpretation 314–15
types 303–6
thermal degradation 73–4
time, emergency procedures 471–3
time sequences 45
topographic charts 55, 56
Tourimei-Meishin expressway tunnel 210
toxic gas releases 357–8
traffic congestion 347–9
traffic management 418, 440–1
traffic regulations 347
trailers 62, 63, 72
train coaches 236–7
see also compartment fires
training 493
emergency procedures 462–4, 468–73, 478
Trans-European Road Network 355
transient simulation 278–82
transverse ventilation systems 129, 132, 133
design for safety 148
mechanical 132–4
Memorial Tunnel Program 207
PIARC recommendations 150
Tunnel Engineering Handbook 145
tunnel fire dynamics 199–320
Tunnel Fire Safety Management System (TFSMS)
model 388–407
autonomy 394
characteristics 390
communication 396–9
concepts 389–99
control 396–9
environment 394–6
externally committed systems 397, 398
functions 390–4
information channels 404
internally committed systems 397, 398–9
key systems 390–4
layered structure 392
organisational principles 404–5
policy implementation 390
proactive safety commitment 396–9
recursive structure 392, 394
relative autonomy 394
safety
audit 393
coordination 390–2
development 393
functional 392–3
policy 393–4
schematic 391
structural organisation 390–6
tunnel linings 55, 57
tunnel operators 408–21
tunnel systems 453–4
tunnel types 111
tunnelling decisions 429–30
turbulence models 172, 176
two tunnel systems 454–5, 477–8
two-shaft longitudinal ventilation systems
132
tyres, ignition 71–2
UK see United Kingdom
unburned fuel ahead of flames on burning object, heat transfer to 186
uncontrolled incidents, development 412
under-ventilated fires see ventilation controlled fires
underground city rail systems see metro systems
UNECE regulations, rail transport 382–3
United Kingdom (UK)
corporate liability 427
HSE tunnel 220, 223
King’s Cross fire 491
West Meon Tunnel 202
see also Channel Tunnel . . .
United States of America (USA)
ASHRAE 154–5
Bureau of Mines 166
Caldecott Tunnel 5, 173–4, 324, 328
corporate liability 426
Ted Williams Tunnel 327
upstream fire temperatures 280–1
UPTUN objectives 214–15
USA see United States of America
validation
CFD modelling 274–5
emergency procedures 461–2
fire safety 307–8
value
potential 306–7
results 196
vehicles
breakdown rules 347–9
damage 59, 62, 63
fires, crucial events 83
involvement 55, 56, 60–2
laboratory examination 76
mass optical density 251
road–rail type 476–7
standards 411
thermal degradation 73–4
velocity, longitudinal flow 245–8
VENDIS-FS models 166, 167
ventilation
analysis 137–8
applying forced 497–8
Bayes’ theorem 187–8
car fires 195
Channel Tunnel 145, 151, 152
common tunnel configurations 149
computational fluid dynamics 138
definition 127
design for safety 144–83
discussion 195–6
ever concepts 128
experiments 159
facilities 137
fans 135–6
fire behaviour 157–65, 184–98
case results 189–95
methodologies 187–8
fire spread 159–62
future 140
guidelines 138–9, 140
HGV fires 189–91, 196
HRRs 158–9, 254
large pool fires 194, 196
longitudinal systems 128–9
mechanical 131–4
medium pool fires 192–4
modelling 166–7
Mont Blanc road tunnel 157
motors 136
national guidelines 140
natural 130–1
older tunnels 144–5
operation during fires 146–57
phenomenological models 167–70
PIARC publications 139
pool fires 191–4, 196, 222–3
rescue operation assistance 502–3
small pool fires 191–2, 193
smoke control 163–5
smoke stratification 147
standards 138–9
state-of-the-art 127–43
St Gotthard Tunnel fire 55, 57
Sydney Harbour Tunnel 134
systems
components 134–7
control 136–7
dampers 136
means of access/escape 439
types 128–34
technology 137–40
testing 139–40
transverse systems 129
velocity 158–9
ventilation controlled fires 162–3, 234
burning process 258–9
fuel-controlled differences 237–41
verification, CFD modelling 274–5
video imaging 107–8
see also CCTV
viscosity models 176
visibility
examples 251–2
longitudinal flow 250–2
tunnels 127
volumetric flow 278
VTT Tunnel 204
waste paper example 80
water–foam deluge systems 120
water delivery 500–1
extinguishing systems 487
mist systems 119, 121
suppression systems 119–22
WEIL (without extra investment level) 400, 401
well-ventilated fires see fuel-controlled fires
West Meon Tunnel fire experiments, UK 202
where, when and why, emergency procedures 456–7
wind tunnels 222–3
without extra investment level (WEIL) 400, 401
witness statements 64, 65–6
world locations 8–9
World Road Association (PIARC) 119–21, 139
yields, combustion products 248–9
zones 168, 258–9
Zwenberg Tunnel 203
Preface. This is the first ever Handbook of tunnel fire safety. That it has appeared at this time is in part a reflection of the considerable growth in tunnel construction worldwide and in part a reflection of concern in society about tunnel safety and fire safety in particular. While much research has been carried out on tunnel fire safety over the years, a text bringing together basic knowledge over a broad spectrum has not existed. This Handbook makes a first effort at filling this gap. It is intended for all those involved in tunnel fire safety, from fire brigade personnel who are at the sharp