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 Préfecte, 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 Delémont 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 FRANTZICHER, 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 healthcare 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, Borás, 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 Marlaire 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 themes 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
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
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He has a degree in Mechanical Engineering from the Instituto Politecnico Nacional, Mexico and
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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
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ings 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 CIB 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,
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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).
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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 Charters 3 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, 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.\textsuperscript{6} 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 \textit{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?

\textit{Figure 0.1. Intermediate methodology A}  
(Redrawn from Reference 3, with acknowledgements to Independent Technical Conferences and University of Dundee.)
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**

- 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
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

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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 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**

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