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Human Behavior as a Key Factor in Tunnel Fire Safety Issues

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Abstract

Recurrent disasters with multiple casualties and important property loss occurred in the last decade in all types of traffic tunnels in Europe and Asia in particular, where existing and planned new tunnels are the largest in number and important for the economy. The aftermath is a new focus on fire safety issues in tunnels on behalf of different authorities, as shown here by a brief review of the European Research and Technological Framework program currently supported by the European Commission. The paper outlines that fire safety level in a tunnel clearly depends on a variety of human factors, other than the simple behavioral aspects of tunnel users confronted to the event of a fire. This is illustrated by facts reported from a number of past accidents in traffic tunnels, including the recent tragedy that took place in the Daegu metro in February last year.

1. Introduction

One apparent factor explaining the number of fire disasters that occurred recently in European tunnels is the sharp increase in traffic (in particular freight traffic in road tunnels), in the relatively old tunnel European network. However, significant accidents have also occurred in more recent links (e.g. the Channel tunnel accident in 1996, despite of the numerous safety studies that are known to have significantly raised the overall costs of construction). Besides, in Europe and elsewhere, new challenges in matter of fire safety issues are going to be faced due to the impressive new projects under completion (e.g. the "big dig" project in Boston [1], or the superimposed roadways tunnel structure for passenger cars traffic on the A86 highway nearby Paris). Moreover, there is also a sharp demand for new underground structures to facilitate transit in urban areas or for crossing geographical barriers on a worldwide basis.

Haack recently presented a picture of the tunneling activity [2] that in particular outlines the following figures :

- Operational tunnels in Europe represent more than 15,000 km in overall length
- Marketing studies have led to estimating the overall potential lengths of new tunnel projects to some 2,000 km in Europe, 650 km in South America and 2,350 km in global Asia.

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Is 'human behavior in fire' a real topic of interest within this background or should the fire safety engineers and authorities and other stakeholders in tunneling still rely mainly on the so-called "hard fire sciences". This is the matter on which the authors are willing to discuss here.

2. The current context

2.1 A recent focus on tunnel safety issues in relation with past accidents

An unexpected series of actual disasters in road and rail tunnels occurred in European countries and Asia in the last decade. These tunnel accidents have been extensively commented, on real time through the media at first and with more progressive and sound feedback in specialized technical literature. Table 1 is a summary of the major tunnel fire events that were deplored from 1995 to time of publishing. At first, when the data are analyzed over the global time scale of traffic tunneling activity, it comes out that dramatic fire accidents in tunnels are increasing in frequency.

<i>date</i>	<i>location</i>	<i>tunnel type</i>	<i>length (m)</i>	<i># deaths</i>
Oct. 95	Baku (Azerbaijan)	Metro	na	289
March 96	Isola del Femine (Italy)	road	150	5
March 99	Mont-Blanc (France-It.)	road	11600	39
May 99	Tauern tunnel (Austria)	road	6400	12
Nov. 00	Kaprun (Austria)	rail (cable)	3400	155
Oct. 01	St-Gotthard (Switzerland)	road	16920	11
Feb. 03	Daegu (Korea)	metro	na	196

Table 1 : the last series of tragedies from tunnel fires

Beyond the overall death toll paid in the mentioned list of accidents, probably the worse series in a single decade period of time to date, the data in table 1, together with more comprehensive work dealing with tunnel accident database management and warehousing [3,4,5] clearly outline basic technical features such as :

- any type of traffic tunnel is concerned (including cable rail tunnels used in ski stations),
- any type of vehicles may be involved (The Mont-blanc disaster of March 1999 alone hit 23 heavy truck vehicles, several cars, vans, emergency vehicles and even one motorbike) [6],
- other scenarios than rolling stock or road vehicles may be involved in a given fire scenario in a tunnel ;
- explosion, although a rare event, is to be taken into consideration (in case of transportation of dangerous goods such as LPG, see lessons from the Palermo (Isolla del Femine) tunnel accident analysis [7] ; apart from the explosion hazard arising from flammable gases and liquids transported through tunnels, terrorism, as recently shown in the metro of Moscow early this year (more than 30 people were reported killed), is another potential cause of an explosion that may be followed by a fire scenario in traffic tunnels ;
- the provision of adequate technical safety measures (emergency ventilation systems, places of safety, alarm systems...) is of essential importance ;
- mass transit systems (e.g. metro tunnels) are a source of concern in the event of a big fire, due to the fact that hundreds of people are liable to be trapped in a single accident, and

that particular difficulties pertain to egress, fire-fighting and rescue in such underground structures (see section 4),

If in a number of cases, technical factors (e.g. inadequate reaction-to-fire performance of materials that are used in rail carriages, problems with brakes on trucks...) largely explain the occurrence of fire events in tunnels, it must also be stated that all those worse case fire scenarios have been influenced in their course of events and consequences by many human factors affecting all stakeholders. Hopefully, the societal perception of risk due to fire in a tunnel has by now drastically been pushed ahead, and this is acting as a booster. Indeed, safety issues must now be treated in any new tunnel project as a priority, including the account of all human factors such as the appraisal of communication means in place to warn users and emergency services, suitability of emergency exits or places of safety (in terms of number, configuration and ease to locate in smoky environment by users), traffic density factors, coordination anticipation of all actors of an emergency response and so forth.

2.2. Human behavior in fires : a growing engineering science

It must be stated that no overview of fire behavior in the context of tunnel safety has been published so far, to our knowledge.

However, learning on a formal basis about human behavior in fires started decades ago, essentially in the framework of conventional buildings, as recalled recently by Shields et al, in their very useful and informative review and prospective work [8] presented at the IAFSS Conference in Poitiers. Shields and Proulx depicted the 'human behavior science' as relatively well advanced in a number of topics related to fire safety issues. Human behavior in fires has now entered the area of scholarly studies in some Universities (University of Ulster, University of Greenwich in England...). The mentioned reference is a good source for a global perception of achievements about human behavior in fires versus time from the mid 50's to end of last century.

Other references, like the SFPE handbook of Fire Protection Engineering [9] , or the collective work edited in the form of a SFPE guidance document compiling engineering science about 'human behavior in fires' released last year [10], make additional powerful resources for those needing an overview of existing global knowledge.

Besides, since 1998, regular conferences have been established in Europe and overseas, focussing on the matter such as those organized by the University of Ulster (Fire-Sert) and University of Greenwich [11,12]

In practice, many aspects governing important safety features in relation with fires in built environment have achieved a fairly good level of understanding. This includes [10] :

- knowledge about : cueing, competitive behavior, impact of crowd density on movement speeds, danger perception, disorientation caused by smoke, importance and modes of awareness of building environment, importance of **pre-movement** time, reduced mobility, aging effects, stress factors... ;
- key roles of communication schemes and incentive messages to help evacuation.

Studies about human behavior in the transportation area have concentrated so far on evacuation problems in boats and aircrafts [13].

3. The current European Research framework on tunnel safety

The European Union, through its 5th RTD (research and technologic development) framework program is actively supporting a number of initiatives that involve, in a joint and coordinated effort, nearly all European experts having proven capabilities in tunnel engineering and associated safety aspects. The 6th FP is expected to support remaining effort to reach what is expected to be the acceptable level of knowledge needed for sustainable development of tunneling activity and related operational issues. Khoury in a recent paper [14] provided a detailed description of what is going on. No less than 7 European consortiums are working in well defined and ambitious research programs or networking activities in relation with safety issues, all of the European authors of this paper are stakeholders in one of several of these. Some data on the mentioned programs are reported in table 2 with their dedicated web sites addresses that allow, once visitors have registered, to know more, track progress of work, and even contribute in some cases as associated partners.

<i>Name of Project</i>		<i>Time table</i>	<i>Web site address</i>
DARTS	Durable and Reliable Tunnel Structures	2001-2004	www.dartSDroiect.net
FIT	Fire in Tunnels (European Thematic Network)	2001-2005	www.etnfit.net
UPTUN	Upgrading fire safety in existing TUNnels	2002-2006	www.uptun.net
VIRTUALFIRES	Virtual Real Time Fire Emergency Simulator	2001-2004	www.virtualfires.org
SIRTAKI	Safety Improvement in Road & Rail Tunnels using advanced ICT and Knowledge Intensive DSS	2001-2004	www.sirtakiproject.com
SAFE TUNNEL	Innovative systems and frameworks for enhancing of traffic safety in road tunnels	2001-2004	www.crfDroiect-eu.org
Safe T	Safety in Tunnels (European thematic network)	2003-2006	www.safetunnel.net

table 2 : major EU sponsored R&D and networking work in progress

All of those projects are indeed considering human factors as a key element in their respective technical programs and deliverables. Other useful European initiatives have recently provided useful deliverables for taking account of human responses in fires and other type of disasters and to develop training interactive tools. These are the NEDIES project (<http://nedies.jrc.it/default.asp>) and the A TEAM project (www.esso.co.at/A-TEAM).

3.2. The FIT activity and human behavior issues

As an example of this, the FIT (Fires In Tunnels) thematic network involves no less than 33 partners from 12 European countries, coordinated by BBRI (Belgium). It aims at establishing and promoting networking activities to optimize concerted efforts on fire safety in tunnels. The current activity essentially consists in warehousing appropriate data, sorting

and organizing them into web accessible deliverables such as series of user-friendly databases about Fires in Tunnels and related matters [15]. Databases involve records on past accidents, computer models, testing facilities available, etc. In addition, the consortium works at the establishment of technical reports (design fires, other appropriate guidance documents). One of those guidance documents in progress is covering the emergency response management and is available for public comments. Figure 1 just illustrates part of work package 1 which consists in the establishment of a database compiling records of useful traffic tunnel accidents and incidents. Today, the short summary list of these records includes nearly 150 entries covering accidents since the beginning of the XXth century, involving tunnel fire incidents or major accidents in some 20 different countries and containing some 35 records with fatalities. The consortium encourages registered users to comment on existing entries and chiefly add missing reports. One breakthrough of this database is actually the number of entries giving sense to some statistical treatment, including on human behavior. As far as the human behavior is concerned, the database manager promoted the introduction of small incidents as well as major accidents, as the former happen sometimes to be unique sources of valuable information on human aspects, and in particular on unexpected -good or bad ! - human responses to fire incidents in traffic tunnels. From this database, other statements regarding fire safety issues in tunnels in relation with human have been identified. One of those is the fact that human factors are potential sources of failures on the whole life cycle of a tunnel, including construction phase, maintenance and refurbishment works and even 'pre-commissioning period' and associated inauguration days.

last update : 30-janv-04		Fire accidents in tunnels: brief overview of real cases. attachment to DB5				
Implemented by : G. Marlaix, INERIS		some new entries compared to previous version				
# of entries 139		some more info on vehicles involved				
# countries involved 28						
# records with fatalities 28						
Date of accident	Name of tunnel	type of tunnel	Country	Length of tunnel	vehicles involved	Casualty
20/01/2004	Ring tunnel, Ljubiana	Road	Slovenia	700 m	1 bus with 50 passengers	?
18/01/2004	Dullin tunnel	Road	France	1550 m	1 bus	none
01/08/2002	tunnel on line Ozieri Chilivani-Decimomannu-C.	Road	Italy	?	freight train	no victim
07/06/2002	52 - interior tube - France	Road	France	650 m		took place during the Love parade attracting more than 1 million people in Berlin streets !
02/06/2002	130 - North tube - France	Road	France	1638 m		
20/05/2002	98 - France	Road	France	4100 m		350 people cut off inside the station during the fire scenario that involved a tram that manage to get out the tunnel section and reach the next station ; difficult operation for the fire brigades
19/05/2002	Ted Williams tunnel, Boston	Road	USA	1200 m	bus	
03/05/2002	tunnel on line Genova Nervio	Rail	Italy	?	freight train	
27/04/2002	Cri'l d'eau tunnel	Rail	France	4200 m	passenger train	
29/03/2002	tunnel on line Nodo di Napoli	Rail	Italy	?	passenger train	
20/03/2002	Valderoy tunnel	Road	Norway	4200 m	bus	
05/03/2002	A 86 tunnel	Road	France	1800 m	special rolling stock	no injured
18/01/2002	Tauern tunnel	Road	Austria	6400 m	1 lorry	no victim
28/09/2000	Oslofjord	Road	Norway	7200 m	truck	no victim
24/08/2000	Saukhopf tunnel Weinham	Road	Germany	2700 m	car	no victim
14/07/2000	Seljestad tunnel	Road	Norway	1272 m		6 injured
08/07/2000	Berlin, Deutsche Oper Stat.	Metro	Germany	not pertinent		no victim
29/05/2000	Cross Harbor Tunnel	Road	Hong-Kong	2000 m		no victim

Figure 1 : example of delivery of FIT thematic network (WPI) so to : www.etnfit.net

This latter view will be developed in due time in the form of a coming presentation to the next 'Interflam' Fire Science and Engineering conference to be held in Edinburgh [16].

3.3. The UPTUN program

UPgrading TUNNELS is another impressive European collective effort to cope with the existing network of tunnels, which was earlier presented as very developed and bearing heavy traffic throughout the EU. UPTUN stands for "Cost Effective, sustainable and innovative UPgrading methods for fire safety in existing TUNNELS". It is a four year research and development project with 41 partners originating from 13 different European countries. The whole project indeed is concerned with human response that the Community may bring to

further extent safety and reliability in existing underground rail and road structures. UPTUN promotes a holistic approach, focusing on research about human factors, and in particular on the interaction of : a) the operator, b) rescue services and emergency teams, c) tunnel users, since it was clearly proven in past accidents that survivability of people trapped in a tunnel, largely depends on adequate coordination in the behaviors and actions of the three categories of people quoted.

WP3 is entirely devoted to the study of the human response and will comprise behavioral analysis of drivers by use of a simulator and tests involving users in a real tunnel facility in which a fire situation is simulated [17,18].

3.4 Investigations about incidents and accidents in tunnels

Major tragedies have been analyzed extensively although sometimes confronted to limitation due to the context of litigation enquiries.

At present time, some aspects coming from records of accidents in tunnels dealing with the human response are well known : e.g. :

- 'traffic lights set to red' is not enough to impede drivers to enter a tunnel portal, in the event of a fire
- passenger interchanges are particularly critical areas in case of a fire emergency [20].

Further careful analysis, as made possible by above mentioned European work may teach more. For instance, keeping inside vehicles seems to be considered in many circumstances as being a safer option than moving out and evacuation to a place of safety or using an emergency exit. Smoky environment is not necessarily perceived immediately as a potential life threat.

The Channel tunnel fire (trans-Manche link between France and UK) (Nov. 1996) [26]

This fire was a real warning (in addition to tremendous source of concerns for the operator in terms of repairs and economical consequences), as it outlined potential problems due to inadequate communications systems and to much complicated procedures in case of an emergency. It also outlined that the worse case scenario involving several HGVs in a single fire scenario was an actual matter of concern and should have been taken into account to define appropriate mitigation measures.

The Baltimore Howard street tunnel fire, USA (July 2001) [19]

This one involved the problem of transportation of dangerous goods through tunnels in urban areas, had significant impact in terms of surface traffic congestion, caused important concern to the fire brigades for access and fire-fighting operations

The Homer tunnel fire (Nov. 2002) in New-Zealand (Nov. 2002)

The fire affected a bus carrying some 50 passengers in a very rustic tunnel without any lighting or safety provisions. The bus driver had the brilliant idea to assist all passengers in their escape through absolute darkness due to smoke by ordering them to chain each other by their hands on their move out of the tunnel : a clear success for which he was officially awarded later on [4].

4. Further discussions about human behavior in fires following early analysis of the Daegu metro fire and some other tunnel fire incidents

4.1 The Daegu fire tragedy and first lessons to be learnt

The accident took place on the 18th of February 2003, close to 10 a.m., at the level of the Jungangno station of line 1 linking Daegu Si to Jung Gu Namil Dong (see figure 2), comprising 30 stations in total.



Figure 2: location of the fire in the city of Daegu, 3^r town agglomeration of Korea

The concerned station spreads on some 10 000 m² of floor area, distributed on three different underground levels : a) third basement contains the platform with access to trains, second basement is the central area with passenger interchange (to opposite platform) and the toll gate, first basement shelters retail stores and staircases. The built environment consists of reinforced concrete structure. Trains circulating in the Daegu metro have an average of about 770 passengers [21].

It is reported that major important facts in the course of events are as follows : a 56 year old arsonist set fire in a first train that had stopped seconds earlier at the platform by igniting a bottle filled with kerosene. Fire spread to arsonist's cloths and a train seat nearby inside one of the car. Then fire is reported to have spread rapidly into the first train (train 1079). Temperature and heat flux patterns were high enough to set alight a second 6 car train (train 1080) that unfortunately stopped some time after on the opposite platform.

Likely to be known by a majority of the attendees, the toll paid in this fire scenario as a result of these course of events is enormous : 196 people were killed, a majority of the fatalities being found in the second train. In addition 147 were injured, including 10 firefighters. Accordingly, property loss is also very high (figure 3). At the present time, the authors wish to keep prudent in the analysis of this drama. An obvious lesson is that nearly all went wrong, due to a series of technical defects and global inadequate human response of all parties involved.

Human response issues under investigation in technical and litigation enquiries being performed, include :

- Erroneous choices in the design phase of rolling stock (reaction to fire performance of selected components) as considered to state of the art,
- Arson act (to be related to mental disability of the guy ?) at the origin of the fire,
- problems relevant to the initial response given by the second train driver (stopped at the platform, took of the key, left the train doors locked that resulted in the fact that nobody escaped from train 1080),

- problems relevant to emergency response management (who has to do what ? and so on...),
- saturation of 'first aid' services available at hospitals nearby
- delayed information to victims relatives and related concerns with the after crisis communication and management.

But the more striking issue is indeed the unexpected behavior of most passengers, waiting strangely in smoke environment as if they were expecting instructions in case of an emergency.



Figure 3 : train car burn out

Figure 2 illustrates the burn out process that affected most of carriages of the trains affected by the fire.



<i>Survivors :</i>	
JUST WAITED	48%
CALLED UP SOMEBODY	20%
MOVED TO OTHER TRAIN CAR	16%
LEFT TRAIN	7%

Figure 4 : analysis of the behavioral réponse of the passengers in the Daegu metro fire

The view in Figure 4 is really hard to believe for a European citizen, however the picture was actually captured by one survivor who escaped the carriage before untenable conditions had been reached. Passengers' first reactions in this tragedy were confirmed from the interview of 146 survivors (see table in the right end side of figure 4) [21]. Nearly one half of the survivors were reporting their first cognitive action was just waiting inside train cars. Some other 20% just called up somebody, people that at first moved to another car in the same train account for some other 16%, and eventually, only 7% of the survivors did just the proper first action that had to be done in such a situation : just leave the train ! This statement

just means that people just react according to cultural context and available information that they were able to make use of, to decide what to do.

4.2 Lessons from other accidents

The next query is how far human behavior in tunnels may be positively influenced by passed disasters in tunnels ? Partial response at least may be delivered from the European scene, by comparing human reactions that were observed, on the one hand in the Mont-Blanc tunnel fire (the first of a series of dramatic fires in tunnels), in 24th of March 1999, and in the other end during the Tauern tunnel fire, that took place in Austria about two months later. It was indeed reported that tunnel users, who were not directly hit by the initial course of event that led to the fire, in the latter accident, rushed out of their vehicles and promptly rushed out of the tunnel, though the portal was not too far from the fire scene. In Korea, a bus fire took place in the *Honggimum* tunnel [25] in Seoul that could have had dramatic consequences if other tunnel users that witnessed the situation had not made their mind to behave with altruism by starting the fire-fighting operations by themselves, making use of the fire hydrants normally at disposal for the local fire service. Still more recently, other situations involving bus fires were remarkably well handled due to extraordinary behavior of the bus drivers, there also in Europe (France, Slovenia), as well as in Oceania (New-Zealand) [4], highlighting the importance of influencing 'common public' decision, when confronted to unusual unsafe environment, such a fire in a tunnel.

Memory or sound based judgment seemed thus in those cases to have influenced positively tunnel users' first response (although quite different in the tunnel fire incidents quoted). It would be dangerous of course to rely only on self education of people either from memory or due to professional background. 'Memory' driven behavioral response is just not enough, it may work in some circumstances just by chance. As a matter of facts, a more systemic approach of human factors must be promoted.

5. Final discussion

At the time, addressing the fire problem within tunnels is much more than considering engineering aspects in relation with time needed for evacuation, as often done in conventional buildings. More basic knowledge on human behavior in tunnel fires is to be learnt from past accidents including happy end events, that must be given the appropriate attention by the operators. The FIT network is there to help in collecting adequately the relevant information and the readers are encourage to use the FIT web site to report on useful incidents that occurred in the past or that might arise in the future. We also encourage them to use the forum organized there for open discussion on the subject.

All stakeholders in tunneling operation (from constructor to tunnel users) must understand the impact of human behavior on survivability in tunnel fires, not only the tunnel users as it was too often the case in the past. Lessons from past incidents also show that differences may anse in behavioral responses of people due to cultural background : this is also to be taken into account appropriately through adequate communication, education and training.

Indeed, education is actually a key factor for a better appraisal of safety problems in relation with the event of a fire in a tunnel. Education is considered essential for all stakeholders including tunnel designers [27], tunnel operators and even regulators. When the question comes to educating the users, should the education of the professional drivers, i.e. rail, bus and coach drivers be a priority for tunnel users ? All of them should receive education in correct emergency behavior, but there is a question of priority to be addressed.

Further research in the field of human responses and performance in tunnel fires is obviously another main conclusive comment to be made.

To the opinion of the authors, adequate experiments, at full-scale in real tunnel environments, such as the one reported by L.C. Boer & J. van Wijngaarden [18] as well as survey interviews of survivors of tunnel fire accidents [22] is considered essential :

- to understand and incorporate behavioral issues of people in the design and operation of all types of traffic tunnels [23,27] (mass transit systems should be a priority target), including differences due to culture,
- to investigate improved options for communications systems within tunnel environments in order to provide instructions to tunnel fire victims, so that they can optimize the usage of evacuation routes to places of safety or emergency exits.

An international interview campaign of survivors of tunnel disasters and incident would be beneficial to gain expertise from each other, and to spare time : such a work is being undertaken by University of Greenwich who are studying human behavior issues associated with the World Trade Center Tragedy.

Finally, establishing, testing and training on emergency plans for a variety of emergency scenarios during normal operations of a tunnel is also of prime importance. Major failures in the past were attributed at least partially to the fact this wasn't done properly. As a result, this has been recently made mandatory, in European countries.

Regular auditing of fire safety management procedures is also to be encouraged.

Harmonization of technical safety measures in addition, as far as possible on a world wide basis is another important target, not necessarily unfeasible...

To summarize, humans in a whole, create problems and can solve them.

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