Safety Science 60 (2013) 35–46

Contents lists available at SciVerse ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/ssci

Analysis of danger management by highway users confronted with a tunnel fire ☆

Sandrine Caroly [a,*], Dongo Rémi Kouabenan [b], Marc Gandit [b]

[a] Laboratoire PACTE (Politique publique, Action et Territoire), University of Grenoble – IEP, BP 48, 38040 Grenoble Cedex 9, France

[b] Laboratoire Interuniversitaire de Psychologie, Personnalité, Cognition et Changement Social (LIP/PC2S), Equipe "Travail, Santé, Changement dans les Organisations" (TSCO), University of Grenoble II, UFR SHS, 38040 Grenoble Cedex 9, France

ARTICLE INFO

Article history:
Received 18 October 2012
Received in revised form 9 April 2013
Accepted 13 June 2013
Available online 17 July 2013

Keywords:
Tunnel fire
Behavior
Perception of risks
Safety
Pivot point method
Information

ABSTRACT

The aim of this article is to show that risk-management behaviors of highway users in tunnel-fire situations are dependent on their knowledge of safety devices and their danger-handling behavior. We hypothesized that the unpredictability of the circumstances in which fires start, as well as drivers' lack of knowledge about safety devices, are likely to have an impact on their behavior. The present study is a detailed analysis of actual fires that have occurred in tunnels, with a close examination of users' evacuation strategies and procedures. In our analysis of 11 tunnel fires, we studied driver behaviors and the strategies they use to cope with a fire. The tunnel users in these fires encountered difficulties both in perceiving signs of danger and in receiving warnings of the danger. The analysis showed that they engaged in a variety of evacuation behaviors and implemented few collective strategies to protect themselves. The problems were related to poor design or equipment, difficulty using safety devices or processing information, or a lack of emergency signals. Some recommendations are made regarding ways of modifying existing prevention and warning devices in view of promoting safer choices among the available options.

1. User behaviors in fire situations

The study reported in this article was aimed at identifying road users' individual and collective modes of managing danger and risks in tunnel fires. This study rounds out two studies on risk perception, accident explanations and behavioral intentions (Gandit et al., 2009; Kouabenan et al., 2006, 2011) in that they touch on a different aspect of danger-coping behavior. More specifically, the present work takes a systemic approach to the study of behaviors observed in actual emergencies, in contrast to the previous studies, which focused on causal explanations and perceptions of risks elicited in a more abstract fashion via interviews of participants in a non-emergency situation (Weill-Fassina et al., 2004).

According to Perrow (1984), accident analyses generally involve first- or second-tier victims, i.e., the workers and co-workers involved, and more broadly individuals in charge of surveillance or process control, technical or support staff (electricians, maintenance workers, etc.), and sometimes even the design engineers.[1] Not much is known about the behaviors of third-tier victims in dangerous situations. Indeed, the role of users has not received much attention in most ergonomics studies on accidents (accidents involving cars, trains, or airplanes) (Spérandio, 1977; Daniellou, 1999) or in research on how people deal with dynamic environments (Hoc, 1996; Cellier, 1987). In the case of driving in highway tunnels, it should be noted that training in the use of tunnel infrastructures and safety devices does not generally extend beyond education in traffic laws: tunnel users (whether occasional or frequent users) are not taught – and know very little about – the safety systems and provisions in the tunnels they drive through. As a result, when confronted with an unexpected situation in a tunnel, they are forced

☆ The studies presented in this article are part of a broader research project on highway tunnel management in case of fire, conducted by three laboratories: the Work Psychology Team of the Social Psychology Laboratory (LPS) at the University of Grenoble II (today LIP/PC2S), the Fluid Mechanics Laboratory at Lyon Central School (ECL), and the Center for Tunnel Research (CETU) based in Lyon. The ergonomic/work psychology team at LPS in association with the Centre of Socio-Technic and Organizational Innovation Reaseach Center (CRISTO) laboratory of the University of Grenoble II (today PACTE laboratory) was assigned more specifically to aspects related to perceptions of fire risks in tunnels, users' behavior, and their perception of intervention means, including ergonomic aspects. The entire project was supported and financed by the Rhône-Alpes Regional Council (Lyon, France), to which we extend our gratitude.

* Corresponding author. Tel.: +33 610031067.
E-mail addresses: sandrine.caroly@ujf-grenoble.fr (S. Caroly), Remi.Kouabenan@upmf-grenoble.fr (D.R. Kouabenan), Marc.Gandit@upmf-grenoble.fr (M. Gandit).

[1] Note that exposure to accidents varies from one industry to another, and that in certain highly complex industries (biochemistry, maritime and air transport, nuclear power), the potential victims are not only the employees (first-tier victims), but also the users of the system (second-tier victims), people located in the vicinity (third-tier victims), and future generations (fourth-tier victims) (Perrow, 1984).

0925-7535/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ssci.2013.06.006

to figure out what to do on their own, either individually or collectively.

Studies on user behaviors in tunnel fires are few and far between. However, more research has been done on fire situations in confined spaces such as subways, large apartment buildings and public leisure spaces (discos, shopping centers, etc.). Although these situations are substantially different from that of users in their car in a tunnel, by comparing the common circulation space and the personal space, we can draw a number of conclusions from these studies in order to understand the behavior of users who are victims of fire in terms of cognition (understanding of safety and rescue systems), evacuation behavior (whether they panic or not) and cooperation between users (individualism versus mutual assistance).

In psychology, there are more studies on fire user behavior. In incidents in buildings where smoke was present, 60% of the people attempted to move through it (Wood, 1980).[2] The movement through smoke depends on sex (64% men, 54% women), smoke spread (64% extensive, 53% less so), environment (64% home, 52% work), time, (65% day, 56% night) familiarity with building (61% completely, 51% less so). When people have to make decisions under time pressure and when subjected to stress, this leads to distortions in the way they process information and affects their ability to adapt to the event. (Ozel, 2001).

In the context of fires in apartment buildings or subways, Canter (1980) and Sime (1980) showed that there were several types of irrational behavior in users: for example, not using all the emergency exits, jumping out of windows, forgetting a member of the family, acting with haste, etc. People do not automatically panic or adopt rational behavior. Everything would seem to depend on how familiar people are with the equipment available, and on their understanding and training (Canter, 1980). Panic behavior emerges when people feel they are in danger (no exit, awareness of the fire's existence, etc.) (Sime, 1980). The behavior of individuals and groups depends on their environment. The psychological environment (Sime, 1999) depends on the transaction between individuals and physical conditions (the fire and the protection and tunnel evacuation structure in fire situations). This psychological environment has an effect on perceptions, attitudes, evaluations and representations underlying behavior. Population evacuation simulation modeling generally focuses on a quantity of individuals and should aim more to take into account different individual and/or collective behaviors depending on the tunnel environment. Most safety messages are based more on the idea of "not panicking" and do not sufficiently consider the psychological processes in relation to the environment (Sime, 1980). For example, how do individuals perceive and act on their environment? How can their understanding of the environment influence individuals' capacities?

Furthermore, evacuation times appear to be crucial and depend not only on the instant when the alarm is triggered but above all on users' behavior. According to Sime (1995), the time it takes to evacuate includes the time needed for people to begin to move and the time it takes them to find and take the exit routes.

There are contrasting results concerning individual behavior and forms of cooperation with respect to evacuation efficiency. The chances of individual survival are smaller when the group encounters difficulties adapting collectively to the situation (Mintz, 1951). Statistically, the number of deaths increases when people try to stay with the same group rather than moving individually or forming other groups for evacuation (Sime, 1985).

In summary, the present article addresses the issue of danger-coping behaviors adopted by users during a tunnel fire. We examine users' representations of risks based on a study of their behavior when actual fires occur in tunnels, with a focus on the evacuation processes and strategies of tunnel users.

2. Objectives of studying tunnel user's behavior during a fire

From a social perspective, a vital purpose of these *studies* is to help improve preventive measures for averting major catastrophes involving the loss of human lives, such as the Mont-Blanc Tunnel disaster of 1999. It is worth noting here that, following that catastrophic event, a new law was passed in France in January 2002[3] promulgating stricter requirements for road-tunnel infrastructures, as well as stronger measures relating to the protection and evacuation of tunnel users. Evaluating the suitability of users' behavior in tunnel emergencies has implications for prevention that go beyond simply designing efficient ventilation systems.

We hypothesized that the unforeseen nature of circumstances causing a fire, as well as users' lack of knowledge about safety devices, are factors that will influence their behavior. One way of understanding tunnel users' behavior is to analyze available clues, surveillance videos, or personal testimonies. We should be able to arrive at a better understanding of the kind of "extreme" behaviors that are adopted in actual emergency situations, but cannot be reproduced in a laboratory setting (Frantzich and Nilsson, 2004; Shield and Boyce, 2004). From an ergonomic standpoint, it should be possible to compare various real emergency situations in order to extract their commonalities and specificities, both in terms of the progression of events and the difficulties experienced by tunnel users in managing the danger (Rasmussen, 1993).

The first scientific focus, related both to ergonomics and work psychology, is to understand users' modes of danger management in a tunnel during an actual fire, in view of better adapting existing prevention measures and guidance. When confronted with a fire in their own vehicle or in another vehicle in the tunnel, drivers often do not even attempt to control or reduce the danger. But they are nevertheless forced to cope with the risk that the spreading fire generates for themselves and for others in their car or in other vehicles. Thus, when analyzing past fires, it is important to understand how users have behaved and what strategies they have used to cope with the fire, in order to relate this to the choices made during the progression of events and the consequences of those choices.

The second scientific focus of the study presented here is to examine the possible emergence of collective activity in a fire situation. During a tunnel fire, do users adopt individual rather than collective strategies? Can we observe behaviors of mutual help or assistance, or on the contrary, do we see panic and self-preservation behaviors, or a selfish desire to protect only the occupants of one's own vehicle? Driving an automobile is generally seen as an individual activity, in the sense that the driver is isolated in his/her own vehicle in spite of being in the midst of more or less heavy traffic. Yet a tunnel-fire emergency brings together a number of drivers who are strangers and are not organized for reacting to this situation. Under such conditions, how and in what ways can collective action be implemented to manage the event? When collective activity does arise, what are the roles of factors related to the tunnel environment, i.e., spatial proximity between users, type of safety devices available, types of alert signals, etc.?

[2] By this method data was collected from nearly 1000 fire incidents and from more than 2000 people who were involved in them.

[3] Law passed on January 3, 2002, put into effect by Decree No. 2002-97 of January 16, 2002, *Journal Officiel*, No. 20, January 24, 2002.

3. Understanding danger-coping behaviors: theoretical point of view and methodology

3.1. Representation and control of danger

Through an analysis of past fires, this study was designed to reveal the actual ways tunnel users manage danger and risks in emergency situations. In particular, we wanted to know to what extent users are able to utilize the information available to them on site when they are in the midst of a tunnel emergency. Does the construction of an operational representation of the fire situation influence their self-protection and evacuation behaviors? Based on the cognitive functioning levels defined by Rasmussen, 1986 (knowledge, rules, skills), Hale and Glendon (1987) outlined the cognitive processes involved in the control of danger. They characterized the control loops that link situational representations to actions. However, in complex situations, interactions between representations and actions do not necessarily follow a rational behavior (Amalberti, 1992; Hoc, 1992).

From a theoretical point of view, almost all studies on the management of danger deal with ways of controlling risky situations in an attempt to avoid danger (Leplat, 2000). In the cases studied here, the majority of users are novices in fire situations; they know almost nothing about the reliability of the system. What we are interested in, then, is determining whether users detect the danger and to what extent – if at all – they are able to build a representation of the situation and decide what actions to take. It cannot be a question of anticipating or judging the acceptability of the danger, since the dangerous situation arises more or less suddenly. The feeling of urgency that ensues can lower the person's chances of adapting in such situations (Stoetzel and Chandessais, 1974). In fact, awareness of the emergency can make a tunnel user all the more disoriented (Orsini and Fraisse, 1959), and time pressure can cause people to totally forget everything they know about how to deal with the situation. This state of affairs reduces their ability to assimilate information (Wright, 1974) and limits the extent of their awareness, leading to "tunnel vision" (Rasmussen, 1986) or a narrowing of attention to the nearest objects or to things within a perceivable range (Nuttin, 1979).

Finally, for several years now, approaches to risk management have tried to look more closely at its collective aspect. In this perspective, risk management can hinge on the chances for collaboration and coordination between members of a group facing a dangerous incident (De la Garza, 1995; Weill-Fassina and Benchekroun, 2000). In the case of a tunnel fire, there cannot be any true group work or work groups; what we may find, though, are various forms of mutual help in coping with the danger, over and above any interventions by surveillance personnel or rescuers. Group activity in the case of tunnel-risk management probably arises in a variety of forms, seeing that people who find themselves in these situations do not really set up voluntary groups with shared norms and expectations. There is no joint diagnosis or decision-making based on tactical reasoning about how to manage the crisis, and there are no phenomena resulting from collaboration between workers of different occupations, as shown in several studies (Samurçay and Rogalski, 1993; De la Garza, 1995; Plat and Rogalski, 2000).

3.2. Analyzing risk management using the pivot-point method

To conduct our study using the "pivot-point method", we relied mainly on the research of De La Garza and Weill-Fassina (1995), based on Hale and Glendon's (1987) model of danger-control behavior. According to these authors, "risk management" can be defined as a set of anticipation, diagnosis, and regulatory processes utilized by the concerned actors before the onset of a dangerous event. The "control of danger", on the other hand, refers to detection, avoidance, and recovery procedures implemented at the moment when the risk becomes real.

A "pivot point" is defined as an event that can disrupt the progression of events and must be managed by the user. An example of a pivot point is when dense smoke emerges from a vehicle following an accident in a tunnel. A pivot point is a turning point in the development of the situation. This method of analysis permits an *a posteriori* reconstruction of the event's chronological development and allows the analyst to identify the representations and decisions of various actors based on an analysis of their behavior. Given the incomplete nature of the information available to us, we often had to make inferences about the cognitive processes underlying the individual and collective behaviors observed. This method can be distinguished from other accident-analysis methods, which tend to rely on logical relationships between elements of the accident-causing situation – as in the causal-tree method, for example – but which do not really take into account the time element and information-processing modes (Weill-Fassina et al., 2004). By contrast, the present method analyzes risk management from a cognitive perspective, while at the same time integrating the temporal dynamic.

3.3. Implementing the pivot-point method

The pivot-point method consists of four major steps:

- Reconstruction of accident scenarios, in order to chronicle the progression of the situation while making connections between the different changes that occurred and the actions of tunnel users. This chronological reconstruction of the accident history is entered into a grid where the different elements making up each phase are noted down and thus the important phases highlighted. The aim is to answer the question "how did it all happen?" in order to determine the different elements making up a stage and the switch from one stage to the next.
- Once each accident history has been placed on the grid with the important stages reconstructed, the major events relating to the circumstances, the fire-management conditions and the actors' behaviors must be placed in chronological order.
- The grid can then be used to identify the pivot points, in order to reveal the key moments in the flow of events while interrelating the external circumstances to the users' "critical behaviors" in the face of danger.
- The list of pivot points stemming from the analysis of several accidents can be used to characterize identical configurations in the management of the event for each accident category. Notably, the points will reveal a certain amount of homogeneity in relations between circumstances, individual behaviors and collective strategies.

3.4. Type of data collected

In order to understand users' behaviors in the face of danger as a function of the representations they build of the situation, we conducted an *a posteriori* analysis of the actual actions taken to manage risk in tunnel-fire situations. Our analysis of risk-management behavior was based on reports and descriptions of 11 incidents. Detailed data from these 11 road-tunnel fires, which we analyzed via the pivot-point method, are presented (see Table 1).

We also obtained two films of past fires from the French Tunnel Research Center (CETU), which we were able to view and put to profitable use. Having "real traces of users' activity", and of what happened in these two situations, made them very important to

Table 1
The 11 fires studied.

Number of fire	Year	Tunnel	Cause	Victims/fatalities
1	1990	Mont Blanc – France/Italy	A truck engine overheats	2 Injured
2	1996	Isola delle Femine Palerme – Italy	Collision: a tanker truck crashes into a small bus and explodes	5 Dead 26 Injured
3	1999	Mont Blanc – France/Italy	A truck (margarine, flour) catches on fire following mechanical breakdown	39 Dead 34 Injured
4	1999	Tauern – Austria	Collision between two cars and a truck	12 Dead 49 Injured
5	2001	Gleinalm – Austria		5 Dead
6	2001	Gotthard – Switzerland	Collision of two trucks	11 Dead 19 Injured
7	2002	Fourvière – France	A car catches fire	None
8	2003	Fløyfjell – Norway	A car runs into a wall (side wall of tunnel)	1 Dead
9	2004	Dullin – France	A car catches fire	None
10	2004	Fréjus – France/Italy	Collision between two trucks, followed by a pile-up of trucks	1 Slightly injured
11	2005	Fréjus – France/Italy	Leaking diesel fuel in an engine – mechanical breakdown	2 Dead

our analyses, and we will rely mostly on these two fires to illustrate our methods and results. For the remaining fires, we essentially worked off official write-ups, newspaper articles, and documents downloaded from the internet. In addition, we were able to follow the trial proceedings of the Mont Blanc tunnel disaster, which took place near the time of our study; this gave us an inside view of the facts and events of this major accident.[4]

In illustration, we will present a detailed analysis of two of 11 fires using the pivot-point method (For reasons of confidentiality, we will call these two fires Fire A and Fire B), in order to demonstrate what actions were taken by users and what means were available to them for coping with the danger. Then, in the interest of brevity, we will present a summary of the outcome of our analysis of all 11 fires.

4. Results

Before analyzing the pivot points of the 11 fires, we performed a preliminary analysis of 33 fires. This enabled us to describe the characteristics of fires in road tunnels.

4.1. Characterizing road tunnel fires

To understand the context of tunnel fires, we analyzed CETU activity summaries and information available in various reports of tunnel fires around the world. From this data, we compiled an inventory of 33 fires in road tunnels reported between 1949 and 2006[5] that had occurred prior to the date of the study, and wrote up general descriptions of them (see Table 2).

The observations made from the reports of these 33 fires pertain to how the fires came about, where they happened, how long they lasted, the likely causes, and how serious they were (victims and/or property damage).

The following points stand out from our study of these reports:

- Most of the disasters involved a truck; there were fewer fires involving only a bus or only car.
- Most of the fires breaking out in a truck stemmed from a collision (12 out of 24 cases involving trucks) or a breakdown (10 out of 24 cases involving trucks). While all the fires breaking out in a bus related to a technical breakdown (all 6 bus cases), the fires breaking out in a car were above all triggered by the vehicle colliding in the tunnel (2 out of 3 car cases).
- The fires caused by a truck lead to more serious human and material damage (11 out of 24 cases) than those caused by a bus or a car.
- The fire lasted longer when it was caused by a truck (8 cases involving trucks lasted over 3 h). This seems to indicate that a fire is more difficult to control when it involves a truck rather than a bus or a car.
- Based on all vehicles, the fires usually lasted less than 3 h (13 out of the 33 cases lasted less than 1 h and 12 out of the 33 cases lasted between 1 h and 3 h).
- Two main categories of tunnel fire consequences can be observed: damage to human lives (injuries or death) without any material damage, or effect on human lives together with material damage. Whatever the vehicle behind the fire outbreak (truck, bus or car), the number of situations with dead or injured persons only and no material damage was smaller (7 cases) than the number of situations combining human and damage to equipment (13 cases). This could point to difficulties controlling and mastering danger.
- The longer the fire lasted, the greater the human and material damage. Indeed, 11 cases lasting longer than 1 h led to substantial human and material damage compared with 3 cases where the fire lasted less than 1 h.

This first set of road tunnel fire characterization data reveals 3 major fire categories, which we will expand on in our analysis of the pivot points in 11 fires: fires resulting in no victims but leading to slight material damage to the tunnel, fires resulting in people being injured but with no damage to tunnel equipment, and fires resulting in human damage (dead and injured) together with substantial damage to tunnel equipment.

4.2. Constructing a pivot-point analysis grid

Two contrasting situations, one without injuries, the other with two fatalities, were reconstructed in detail, in terms of both the progression of events and the behaviors of users. We compared the fire scenarios on the basis of the partial data available for our analysis (accident reports and videotapes taken by several cameras mounted in the tunnels).

Here, we present the characteristics of the grid with elements relating to the fire circumstances or environment and the major

[4] Given that our study was conducted during the period of the lawsuits of the Mont Blanc tunnel-fire victims, we decided not to discuss them in detail in this article because (1) not all elements of the investigation were available at the time and would depend on court proceedings, and (2) this fire was widely publicized, which meant potential distortions of the facts due to the actors' understanding of events in accordance with their particular situation and the direction the discussions were taking in court.

[5] Only those fires that occurred in highway tunnels were analyzed. The evacuation of a subway, a train, or a cable car is a considerably different situation as far as risk management is concerned.

Table 2
Characteristics of the 33 tunnel fires from 1949 to 2006.

Time fire lasted	Human and material consequences	Collision with other vehicles	Types of vehicles involved								
			Trucks Probable causes		Bus Probable causes			Cars Probable causes			
			Breakdown	Crash	Collision with other vehicles	Breakdown	Crash	Collision with other vehicles	Breakdown	Crash	Total
1 h	No injuries or deaths		XX			XXXX			X		7
	Injuries or deaths		XX							X	3
	Injuries and damage to tunnel										
	Death and damage	XX				X					3
1–3 h	No injuries or deaths		XXXX			X					5
	Injuries or deaths	X		X						X	3
	Injuries and damage to tunnel										
	Death and damage	XXX		X							4
More than 3 h	No injuries or deaths	X									1
	Injuries or deaths	X									1
	Injuries and damage to tunnel		X								1
	Death and damage	XXXX	X								5
Total		12	10	2		6			1	2	33

phases of the fire, as well as the actions undertaken by the different protagonists present in order to manage the fire. This grid stems from an iterative process to reconstruct the fires analyzed based on a chronological reading of the events (see Tables 3 and 4 for illustration).

This grid has five columns and five rows. The columns indicate the five major phases of the situation: stopping the vehicle, vehicle catching on fire, alert given by the surveillance station, evacuation of the tunnel, and intervention by rescuers. The rows refer to the conditions in the tunnel area, the signal situation, and the control actions undertaken by users or operators in charge of surveillance and rescue. More specifically:

- Row 1 indicates the current state of the signals.
- Rows 2 and 3 indicate, respectively, the actions taken by the driver to control the danger, and the consequences (here, spreading of smoke).
- Row 4 indicates the main danger- and risk-control actions taken by surveillance and rescue operators.
- Row 5 indicates the behaviors of other tunnel users in coping with the danger.

4.3. Analysis of the fire occurring in Tunnel A

4.3.1. The scenario of Tunnel A fire

The scenario of Tunnel A fire can be outlined as following:

- *Phase 1*. The tunnel has a double-tube design, with a length of 1853 meters. The incident takes place within the tube running from south to north. A vehicle stops at a distance of 1250 m past the tunnel entrance, near where Camera 9 is located. The driver enters a recess and reports the emergency. Traffic is blocked by the stopped vehicle. The CCS (central control station) detects the incident.
- *Phase 2*. The driver uses an extinguisher to try to put out the fire at the front end of the vehicle from where the smoke is issuing. No one comes to help. The smoke gets thicker, but it is still possible to see daylight in the distance, suggesting that the tunnel's exit is near. Several other vehicles pass in spite of the smoke. The passengers in the burning vehicle get out and head on foot toward the tunnel entrance. The CCS activates the ventilation system.
- *Phase 3*. The tunnel surveillance station gives the alert by turning on the sign "Do not enter tunnel" and broadcasts the alert message over the radio. Farther ahead in the tunnel (Camera 5), a car stops and the driver gets out and warns other users. In another section even farther ahead (Camera 3), a car stops but the driver doesn't get out of the vehicle. Despite the "Do not enter" sign at the tunnel entrance, cars continue to enter. The signal lights are located on the ceiling, so they are not easily seen by drivers. A traffic jam occurs inside the tunnel. The smoke coming from the burning vehicle gets thicker and thicker.
- *Phase 4*. At this spot in the tunnel (Camera 5), the smoke is not visible. There is no sign indicating the exact location in the tunnel (number of kilometers already driven and kilometers remaining to reach the exit), nor any information on the distance from the fire. Various evacuation behaviors are observed. Some users head towards the tunnel entrance on foot. Others make calls on mobile telephones and stay where they are. One person smokes a cigarette and looks in his briefcase in the front-seat area of his vehicle, another takes his suitcases that are in the car. A family gets out of their car for a few minutes, walks around, and then gets back in their car. The self-evacuation process lasts more than 25 min.
- *Phase 5*. The firefighters intervene 40 min after the burning vehicle had stopped. They have trouble getting through due to vehicles parked on the right and left. Some users walk on the sidewalk and head toward the tunnel entrance. Others make a U-turn with their vehicles.

4.3.2. Analysis of Tunnel A fire with grid and indication of pivot points

The analysis of Fire A using a grid makes it possible to identify several pivot points which may possibly have triggered the situation's aggravation. The pivot points are represented in the Table 3 by gray areas.

Table 3
Synthesis of pivot points and users' danger-coping behaviors in Tunnel A fire.

State of situation and actions of protagonists	Development of situation				
	Phase 1 Vehicle stops	Phase 2 Vehicle on fire	Phase 3 Alert by surveillance station	Phase 4 Evacuation of tunnel	Phase 5 Intervention by rescuers
1. Environment: signals			Signal lights (up high on ceiling)	No information telling people where they are in tunnel or distance between one's location and place of fire	
2. Control of danger by driver	Camera 9: Driver gets out of his vehicle and enters a recess	Driver tries to put out fire with extinguisher but fails			
3. Spread of smoke in area	No smoke	Smoke, but exit visible (daylight in the distance)	Camera 9: Smoke is thick	Smoke is thick	
4. Control of danger and risk by surveillance station and rescuers	Computerized automatic detection – opening of recess	Activation of ventilation system to exhaust smoke			
	Activation of "Do Not Enter" sign at tunnel entrance		Rescue vehicles enter tunnel, have to do their maneuvers		
			Broadcast of warning message over FM radio		Impeded by vehicles stopped on road
5. Behaviors of tunnel users	Traffic impeded	Passengers of vehicle evacuate	Information not heard	Cameras 5 & 3: Smoke not visible to users at this location	Users continue to evacuate on foot
		35 vehicles pass in left lane	Vehicles continue to enter and create traffic jam		Others start *** backing up/making U-turns*** with their vehicle
		Camera 5: Some people evacuate on foot	Camera 5: A single vehicle stops; it's driver walks forward in line-up and gives the alert	Others do not move and get back into their cars	No one injured
		Slowing, but no one stops to help driver of smoking vehicle	Camera 3: Another vehicle stops, driver stays inside	Camera 3: Some vehicles start *** backing up/making U-turns***	

In Tunnel A fire, the pivot points are as follows:

- The driver of the burning vehicle is not able to put out the fire with the extinguisher.
- The signals placed up at the top of the tunnel are not easy to see. This leads to failure to get information about the tunnel situation, so cars continue to enter the tunnel in spite of the prohibition.
- The warning message is heard only by some people who have their radio on (design of the technical device for informing tunnel users). Thus, the information is not received by everyone at the same time; this causes users to wait for more detailed information and to hesitate before evacuating.
- The smoke gets increasingly thick but cannot be seen in all parts of the tunnel. This causes difficulties in evaluating the risk and leads to a variety of evacuation behaviors.
- What's more, the lack of indicators as to where people are located in the tunnel in relation to the fire does not help to promote evacuation behaviors.
- Users abandon their vehicles parked in the road, making it difficult for rescue vehicles to get by.

Thus, the people in the tunnel generally did not build a representation of the dangerous situation. Their behaviors indicate that they were more concerned with the road and traffic than with the warning signals and safety instructions. Individual attempts at self-preservation appeared: passing other cars when the exit was visible, turning around when the entrance was near. We observed a failure on the part of tunnel users to adopt helping behavior in coping with the dangerous situation. The fact that the users were not aware of the danger prevented them from taking the proper protective or preventive actions.

4.4. Analysis of the fire occurring in Tunnel B

4.4.1. The scenario of Tunnel B fire

The scenario of the Tunnel B fire can be outlined as follows:

- *Phase 1*. Around 6:00 p.m., a fire breaks out in a semi-truck hauling tires, when the truck is about halfway through a 12.8-km-long tunnel that connects France to Italy. At Kilometer 2.7, a cattle truck passes the semi – which is belching black smoke on the left side of its cab – and informs the safety operators when coming out on the French side. The driver of the tire truck stops at Kilometer 2.9 and gets out of the truck.
- *Phase 2*. The driver runs in the tunnel towards the Italian side, passing by a call-box recess without stopping. The driver gestures to a tanker truck that is passing by. He comes to another recess, pushes the SOS button, picks up the telephone, and talks to the surveillance operator for 50 s. He does not speak French very well. The tanker truck passes the truck that is on fire, and the displacement of air causes another fire to break out on the right side of the burning truck. In the other direction, a car and a refrigerated semi-truck go by the burning truck, passing through thick smoke.

Table 4
Synthesis of pivot points and users' danger-coping behaviors in Tunnel B fire.

State of situation and actions of protagonists	Development of situation				
	Phase 1s Vehicle stop	Phase 2 Vehicle on fire	Phase 3 Alert by surveillance station	Phase 4 Evacuation of tunnel	Phase 5 Intervention by rescuers
1. Environment: signals		Safety devices not used		Signs indicating location in tunnel	
2. Control of danger by driver	Driver stops his vehicle late	Driver runs toward exit on Italian side and gestures to vehicles he passes	Truck bursts into flames Driver enters a recess He doesn't speak French	Driver tries to get to scrap-metal truck	
3. Smoke situation	Smoke comes out of cab of truck	Smoke is thick	Can't see through smoke	French side: Zero visibility due to smoke *Italian side:* Smoke thick as far as camper	Two explosions *French side*: zero visibility due to smoke
4. Control of danger and risk by surveillance station and rescuers			Closure of barrier Alert message broadcast over FM radio Activation of ventilation system in France-to-Italy direction		*French side*: Rescuers are blocked by the Mercedes A safety operator directs drivers in making U-turns *Italian side*: Three safety operators try to warn people in scrap-metal truck
5. Behaviors of tunnel users	A driver tells someone at toll booth about the smoke	Three vehicles pass in left lane (1 tanker, 2 cars)		Three drivers push SOS button Several cars make a U-turn *French side:* A truck driver goes into a shelter Mercedes passes and makes a U-turn, blocking the road *Italian side:* A truck driver hurts himself when getting out of his truck and walks back in tunnel Two people do not get out of their scrap-metal truck A camper backs up to a shelter, then makes a U-turn Some cars pick up people on foot	*French side*: Mercedes parks in opposite direction from line of traffic Two women hesitate about evacuating Cars making U-turns pick up truck drivers who are on foot *Italian side*: The two people in the truck try to get out but are blocked by smoke (die of asphyxiation)

- *Phase 3*. The surveillance operator activates the system that closes the barriers at the toll booth. He informs users of the fire through a warning message over FM radio, and turns on the ventilation system in the France-to-Italy direction.
- *Phase 4. On the French side*, 19 vehicles are blocked behind the burning truck. There is no smoke. Several vehicles make a U-turn. Two users in two different places push the SOS button. A truck driver gets out of his truck, puts on a safety jacket, and tells the vehicle behind him to turn around. The truck driver gets back into his truck and backs up to park it in a shelter area. A Mercedes overtakes several vehicles until it is blocked by a bus and then makes a U-turn. *On the Italian side*, nine vehicles are stuck in front of the burning truck. The smoke is too thick to see through. A driver of a truck carrying cheese gets out of the cab, hurts his leg on the step while getting down, walks alongside his truck toward Italy, and then continues walking alongside the tunnel wall. Behind, two foreign truck drivers of a scrap-metal truck do not get out of their vehicle. The driver of the burning truck walks back as far as the rear of the scrap-metal truck but cannot go any farther to inform the drivers due to the dense smoke. A camper behind it backs up as far as a parking area and makes a U-turn. The driver of a tanker truck hauling glue, located behind the camper, gets out of his truck and pushes an SOS button. He gets back into the vehicle and makes a U-turn. Three other vehicles, one of which has just entered the tunnel, make U-turns.
- *Phase 5. On the French side*, rescue vehicles are blocked by the Mercedes that made a U-turn, and have to park on the wrong side of the road in the lane of blocked vehicles in order to free up the passage. Two explosions occur, prompting more drivers to evacuate the tunnel. Two female occupants of a vehicle farther ahead want to make a U-turn, but some people getting out of a van talk them out of it. The women leave their vehicle, head towards France on foot, then get into the bus that is backing up. Next they get back out of the bus, return to their car, and make a U-turn. A tunnel patrolman organizes U-turns up to where the bus is. The truck drivers abandon their vehicle and get into the cars making U-turns. The self-evacuation is accomplished in 7 min and 30 s. *On the Italian side*, two people get out of the scrap-metal truck and are trapped by the smoke. The

Table 5
Synthesis of types of fires. Evacuation behaviors of tunnel users, and pivot points.

	State of situation and action of protagonists// points pivots	Type 1					Type 2					Type 3					Total
		Asphyxiation, death (Mont Blanc 1999, Gotthard, Frejus 2005)					Injuries (Tauern, Fourviere, Mont Blanc 1990, Isola-Palerme)					No victims, property damage (Gleinalm, Floyjell, Dullin)					
		Environment signal situation	Control of danger by driver	Smoke situation	Control of danger by surveillance station and rescuers	Behaviors of users	Environment Signal situation	Control of danger by driver	Smoke situation	Control of danger by surveillance station and rescuers	Behaviors of users	Environment Signal situation	Control of danger by driver	Smoke situation	Control of danger by surveillance station and rescuers	Behaviors of users	
1.	Poor design of tunnel (curving, on a slope, slippery pavement, etc.)	X		X	X		XXX			X		X					8
2.	Poorly designed equipment (signal lights on ceiling, lack of lighted signs, etc.)	XX					XX										4
3.	Difficulty using safety devices	X	X			X	X	X			XX	X					8
4.	Rapid spread of smoke			XXX					XXXX					X			8
5.	Difficulty in providing information about the danger (from CCS to users, between users)		XX		XX					XXX					X		8
6.	Poor design of warning system				XX					XX							4
7.	Smoke not visible			XX		X					X						4
8.	Difficulties in perceiving the danger (driver stops too late, staying in car, etc.)		XXX		X	XXX				X	XXX		X		X	X	14
9.	Difficulty controlling the danger (maldaptive behavior by rescuers and users)		XXX		XXX	XX		X		XXX	XXX		X				16
10.	Difficulties with signs and signals (lack of information given by signals)					X										X	2
11.	Heavy traffic	XX					X					X					4
12.	Explosion								X					X			2
13.	Problem of communication language		XX														2
14.	Consumption of alcohol, drugs, medication by driver		X														1
	Total	6	12	6	9	8	7	2	5	10	9	3	2	2	2	2	85

three tunnel safety operators, having trouble themselves, do not manage to get them to a shelter. The two truck drivers will later die of asphyxiation.

4.4.2. Analysis of Tunnel B fire with grid and indication of pivot points

The pivot points of Tunnel B fire are represented in the Table 4 by gray areas and are as follows:

- the driver of the truck that caught on fire failed to use the available safety devices,
- violation of safety rules by the two people in the scrap-metal truck,
- the inability to evaluate the risk due to the fact that the smoke could not be seen,
- failure of tunnel users to detect the alert broadcast over FM radio,
- the passing of vehicles at the onset of the fire caused an expansion of the fire,
- the behavior founded in numerous U-turns confirmed the existence of individual attempts to manage the situation,
- poor mastery of the foreign language,
- incident of the truck driver who injured his ankle when getting down from his truck and lack of help from others.

In Tunnel B, the users were mainly relying on individual strategies and actions (making a U-turn, getting out of/back into their vehicles, etc.), with a few interactions with other users. In this fire situation, as much on the French side as on the Italian side, some collaboration did emerge between truck drivers and car drivers (people on foot getting into a car making a U-turn). Also, the tunnel safety operators organized more evacuation procedures once on site. The deaths of the people from the scrap-metal truck were the result of several pivot points: not using safety devices, not hearing the alert and difficulties related to mastery of the language.

From a cognitive standpoint, we can see two pivot points that are identical to the ones found in the two fire situations analyzed (Tunnel A and Tunnel B): a variety of behaviors followed (U-turn, evacuation on foot, etc.), poor knowledge of how to use the devices, failure to see that they were there. The analysis of these two fires showed that when a fire started up in their vehicle, the drivers exhibited two types of behavior: informing the surveillance station and trying to extinguish the fire themselves (Tunnel A), fleeing the fire and alerting others (Tunnel B). However, the overall accident pattern was nearly identical in both situations: diversity of individual behaviors suggesting non-identification of the danger signs, and uncertainty about what the warning message meant, probably caused by difficulty building the right representation of the danger. In both cases, the lack of an accurate representation of the situation made individual risk-handling actions difficult, but no collective helping strategies emerged either. On the other hand, there were differences between the two fires as to their evacuation modes. The outcomes of both disasters were different too, since in the first case there were no victims whereas in the second two people died.

4.5. Pivot points from the analysis of 11 fires: list per type of fire

In all, we analyzed 11 tunnel fires using the pivot-point method outlined above and demonstrated through the case of two accidents. The result of pivot-point analysis of the 11 tunnel fires pointed out the existence of several patterns or types of fire occurring in road tunnels (see Table 5).

We based our analysis on the 3 typical categories stemming from our preliminary analysis of 33 accidents (see Section 4.1): situations leading to deaths with substantial material damage to tunnel infrastructure (Type 1), situations resulting in injuries with damage to tunnel equipment (Type 2), and situations where nobody is injured or dies with slight damage to tunnel equipment (Type 3). Applying this incident type categorization to the 11 fires showed us that 3 incidents belonged to type 1, 4 incidents to type 2 and 4 incidents to type 3.

Each type of fire is characterized by a set of pivot points. Our analysis underlined several noteworthy aspects:

– there are more pivot points in type 1 fires (41 pivot points) than in type 2 fires (33 pivot points) and type 3 fires (13 pivot points).
– In Type 1, many pivot points can be seen to concern difficulties perceiving danger (7/15). These are situations where there are dense traffic and communication problems linked to the use of foreign languages. Furthermore, the way the driver behind the event (breakdown or accident) controls the danger seems to be a determining factor in terms of how the situation might worsen (12 pivot points out of 41 for type 1 while this aspect only accounts for 2/33 for type 2 and 2/13 for type 3).
– In types 1 and 2, all the other actors have great difficulty controlling the dangerous situation (8/17 for type 1 and 7/17 for type 2). It should also be noted that in both situations, the smoke spreads quickly (3/8 for type 1 and 4/8 for type 2).
– In type 2, issues relating to tunnel design (e.g. curves or slopes) have a negative effect on signposting in the environment (3/7). The signage in the tunnel is hindered by the environment (7 pivot points out of 33 for type 2 compared with only 6/41 for type 1 and 3/13 for type 3). Furthermore, the surveillance station's difficulty controlling the danger is greater in a type 2 situation (10 pivot points out of 33 for type 2 compared with only 9/41 for type 1 and 2/13 for type 3).
– In types 2 and 3, user behavior seems to be a determining factor in the way danger is managed (4 pivot points out of 13 for types 3 and 9/33 for type 2 compared with 8/41 for type 1).

In short, danger-control strategies are not implemented by the driver, by tunnel safety and surveillance operators, or by other tunnel users, because of difficulties related to poor design of the tunnel or equipment, improper use of safety devices or information management, or a lack of proper signals and signs.

5. Discussion and conclusion

Using the pivot-point method to analyze risk-management behavior, we were able to interrelate cognitive processes and fire circumstances. The detailed analysis of the 11 fires according to this method allowed us to identify several factors at work in the different types of fires:

- *Aggravation of circumstances of the fire-causing event*. Delayed detection of the fire by the vehicle driver or other drivers arriving at the accident scene is mainly related to problems noticing the danger signs.
- *Non-use of safety devices farther in the tunnel where the fire develops*. Users do not know what they should do in case of fire, nor do they know when or how to utilize the protective and emergency systems.
- *Failure to receive the fire warning*. The order to evacuate sent out over the radio is not heard by all users. The person who has the information could inform other users of the alert but does not always do so. The fact of not hearing the alert prevents users from rapidly engaging in behaviors of avoidance or retreat.
- *Disorientation during the fire*. Building a representation of the risk is difficult when the smoke is not visible from the spot where the user is located, especially since users are not always able to pinpoint their own location in a tunnel (near or far from the event). This can cause them to be hesitant about what they

ought to do. Dangerous individual behaviors can then appear, such as trying to pass other cars or getting out of one's vehicle and then returning to it. Victims believe that their vehicles provide shelter and do not perceive the danger.
- *Poor evacuation procedures*. Safety operators are not present to organize rescue operations, and thick smoke reduces visibility to zero, leading to difficulties in evacuation. We find individual self-protection behaviors such as making a U-turn with one's vehicle to get away from the danger. People who stay in their cars from the start feel ill from the toxic smoke by the time they decide to go to a shelter.

The study presented in this article points out some of the factors at play in risk detection and identification during tunnel fires, as well as the individual and collective behaviors executed to manage evacuation of the tunnel. By examining tunnel users' behaviors in the face of danger (fleeing, evacuation, informing other users, etc.), we observed that their behaviors reveal difficulties in building an *operational representation* of various aspects of the fire situation. Information on the nature of the danger and ways to handle it is not always available or readily accessible: the presence of smoke is not an immediately perceivable given in all situations, and this may explain why some users do not flee or seek protection. Indeed, according to Bryan (1999), perception of smoke is a determining factor in user evacuation behavior. Many drivers are used to being stuck in traffic jams without knowing why. Yet, a fire can spread and create a very critical situation, even within the short span of five minutes. According to Sime (1986), decision-making in an emergency situation can be hindered by the physical environment when this does not provide enough information about developments relating to an event or incident. Tunnel structure design (space, equipment, etc.) does not sufficiently take into account users' psychological needs, especially their need to find information about the environment in which they find themselves. For example, aspects relating to an individual's sense of place are bound up in the role of a building in that person's life experience. "The building may be imbued with particular qualities or physically modified by the eventual building users" (Sime, 1986, p. 60). In the case of tunnels, for example, it is easier to use a telephone located in a niche if that telephone works and looks like a familiar telephone.

Contrary to what has been shown in studies on accidents occurring at the workplace, users of tunnels are not aware of the risks incurred in a roadway tunnel, nor do they have any experience using protective and rescue equipment; this makes it impossible for them to rely on anticipation or caution strategies. Instead, we find various forms of ad hoc planning and trial-and-error attempts, which amply demonstrate tunnel users' poor control over the situation.

The pivot-point analysis showed that users have trouble building an accurate representation of the emergency situation, thereby causing a great many of their behaviors to be poorly adapted to controlling the danger.

Furthermore, a system of mutual aid or assistance between users does not emerge in the portion of the tunnel ahead of the incident, and this kind of planning can turn out to be difficult to achieve in a dangerous situation. Not all users have the same amount of information about the event (some don't know what's happening, others have heard alert messages broadcast over FM radio, still others have seen a message displayed on the signals at the tunnel entrance or have been informed of the fire by rescue teams, etc.). For all these reasons and various others related to the lack of an organized effort, we find a greater number of individual actions than collective strategies. According to Sime, 1983, when members of a group belong to the same family, the evacuation strategies are organized differently compared to when the group is made up of persons who do not know each other and have no emotional ties: "Family members tried to adopt an optimal strategy for group rather than individual survival" (Sime, 1983, p. 21). In an ambiguous situation, individual behaviors can above all be observed but in this situation members of the same family tend to adopt group behaviors when they evacuate. In a tunnel, people do not normally belong to the same family, except those traveling in the same car perhaps, and are in an unfamiliar context, which may explain one of the difficulties building collective evacuation strategies.

The results of the present study are useful in making a number of recommendations regarding the design of safety devices and the information made available to tunnel users, with a major concern being to take user behavior into account and help tunnel users take actions that promote risk identification and effective processing of warning and evacuation messages.

Certain recommendations could deal with *the development of safer traffic standards and regulations, and more suitable and more reassuring protection systems*. For example, safety provisions and equipment in tunnels should be standardized (how recess doors are opened, for example), as should tunnel-ceiling lighting. It should be mandatory to have a concrete railing to mark off two-way traffic in four-lane tunnels, and there should be an air shield so that ventilation does not move smoke in one direction of the tunnel, etc.

Thus, the organization of fire-risk prevention should not rely solely on safety measures related to tunnel evacuation, but should also include provisions to promote dissemination of warning messages. Indeed, *effective management of warning information* is just as important as that of evacuation information, and these two kinds of information are tightly linked. It seems necessary to rethink emergency procedures in a way that would favor the implementation of individual and collective danger-coping actions. In particular, how can one communicate with all tunnel users rather than just certain individuals? How can better reception of danger signals be achieved? In other words, how can we ensure that all people involved find out about the fire? In our view, giving official information to everyone at the same time would promote safe behavior. For example, the fire warning could be sent out by visual signals, such as blinking red or orange lights installed on the right and left walls of the tunnel, and signs inside the tunnel with messages such as "Disabled vehicle at Kilometer 2 – Keep Right" could be installed in several sections of the tunnel, etc. These recommendations have been applied in tunnels built since the 2002 law was introduced, under the initiative of the CETU. Indeed, their application coincided with this study.

Although safety devices and provisions have a definite impact on the behavior of the tunnel user, research on tunnel fires for many years now has mainly dealt with the effectiveness of ventilation systems. Simulations have been done on technical aspects (smoke infiltration, fire-resistance properties of materials, etc.) but they have not taken human behavior and risk perception into account enough (Altinakar et al., 1997; Bryan, 1999; Mos, 2005; Soulhac et al., 2008). Viewed from the social and scientific perspectives taken in this study, effective management of risks related to road-tunnel fire lies in understanding the actions of users who find themselves in such a situation. The information-processing modes observed in these situations suggest that the way danger signs are detected and risks are identified depends on the representations of danger situations built by users. Our studies reveal the difficulties tunnel users have in making a trade-off between the use of poorly understood protective equipment in a dangerous situation they have trouble perceiving and the behaviors they are supposed to adopt in the face of danger. In a critical fire situation, the actions of users are governed by probable feelings of panic and strong time pressure. Our results suggest that, in reality, users do not really panic: some stay in their car or hesitate to actually evacuate (for example, they get out and then get back into their car). These results confirm data about user behaviors in other fire situations, as mentioned in part 1, i.e. knowledge of evacuation depending on training and familiarity with the environment and absence of panic behavior in all situations (Sime, 1980; Wood, 1979). The distance from the fire, the belief in the structure's safety and the spread of smoke are the first features taken into account by users in the evacuation decision-making process (Bryan, 1977). The environment must provide information that can be seen and is adapted to the episodic nature of users' behavior (Sime, 1983) and their experience with fire.

This research confirms also the relationships between users' representations of danger, control of danger, and risk management in emergency situations. Hale and Glendon's (1987) model of behavior involving control of danger describes the protection and prevention strategies and procedures of subjects facing danger, starting with the different stages of the perception of the danger up to the actions taken to control it. In the case of tunnel fires, it is not clear that users identify the danger. From an ergonomic point of view, the cognitive mechanisms at play in the management of tunnel-fire risks cannot be rooted in anticipation (due to task unfamiliarity), but consist instead of evaluating the danger and making a diagnosis as to how to protect oneself or get out of the tunnel. We cannot really speak here of "control" over the different parameters of the situation. The fact that tunnel fires are rare does not help in foreseeing the possible things that might occur and that could prove to be more or less difficult for the victim to manage (problem of building a representation of the danger situation, lack of experience handling fires in general, etc.). In this situation, it would be useful to be able to act on the tunnel environment so that the people in danger can build up their ability to protect themselves and evacuate the tunnel. Users should therefore be taken into account in tunnel design, safety architecture, etc. (Sime, 1986).

This research also shows that it is difficult to engage in collective action aimed at controlling danger. In our approach, where a road tunnel during a fire is seen as an open dynamic system (Rogalski, 2003; Samurçay and Delsart, 1994), every tunnel user who is informed of the fire and of the means at his/her disposal becomes a full-fledged actor in the rescue system. It is clear that when a fire starts up in a tunnel, not all users can be warned directly by the surveillance operators. On the other hand, those who do find out about the fire can provide vital help to other tunnel users.

One of the limitations of this type of after-the-fact study lies in the impossibility of interviewing victims about the progression of events and the development of the situation. For this reason, the information we gathered is not comparable to what could be learned through a field investigation. The information used for our analysis had already been processed and therefore did not provide a complete picture of the emergency situation and its management by tunnel users. However, the observed data were useful in making inferences about how the risk was managed.

An analysis of actual behaviors in the face of a dangerous fire can only be done by examining real fire situations. However, one of the limitations of this study is precisely the situations we observed. First of all, we were not able to obtain a large amount of information about the fires from surveillance videos and written documents, and secondly, unlike serious cases, past fires that are well-managed by users and surveillance operators are not always well documented.

Future research on this issue could attempt to identify the conditions in tunnel environments that promote a realistic representation of risks by users and better knowledge of available means of action. Indeed, the decision to evacuate can only be made by users after they have been given the necessary information and have assessed their current and upcoming risks (Samurçay and Rogalski, 1993). The pivot point method would appear to be useful for analyzing how individuals take on board information in their environment and for understanding their interactions with other users. This tunnel fire analysis suggests that a number of environmental features should be modified and the information messages transmitted by tunnel agents should be adapted so that rescue and evacuation are better organized.

References

Altinakar, M.S., Weatherill, A., Nasch, P.H., 1997. The use of a zone model in predicting fire and smoke propagation in tunnels. In: 9th International Symposium on Aerodynamics and Ventilation of Vehicle Tunnels. BHR Group, Aosta Valley, Italy.

Amalberti, R., 1992. Safety in risky process control: an operator-centered point of view. Reliability Engineering and System Safety 38, 99–108.

Bryan, J.L., 1977. Smoke as a Determinant of Human Behavior in Fire Situation. U.S. Report of Department of Commerce National Bureau of Standards, Washington, DC 20234.

Bryan, J.L., 1999. Human behavior in fire: the development and maturity of a scholarly study area. Fire and Materials 23, 249–253.

Canter, D., 1980. Fires and Human Behaviour – An Introduction. In: Canter (Ed.), Fires and Human Behaviour. John Wiley and Sons, New York, pp. 1–12.

Cellier, J.M., 1987. Study of some determining elements of control orientation in a bus traffic regulation. Ergonomics International. Taylor and Francis, London, pp. 766–768.

Daniellou, F., 1999. L'expertise judiciaire sur les accidents graves: un témoignage. Performances Humaines et Techniques (November–December) 1999 (102), 11–13.

De la Garza, C., 1995. Gestion individuelles et collectives du danger et du risque dans la maintenance d'infrastructures ferroviaires. Doctoral Thesis in Ergonomics. LEPC-EPHE, Paris 5.

De la Garza, C., Weill-Fassina, A., 1995. Méthode d'analyse des difficultés de gestion du risque dans une activité collective: l'entretien des voies ferrées. Safety Science 18, 157–180.

Frantzich, H., Nilsson, D., 2004. Evacuation experiments in a smoke-filled tunnel. In: 3rd International Symposium on Human Behavior in Fire. Belfast, UK, 1–3 September 2004, pp. 229–238.

Gandit, M., Kouabenan, D.R., Caroly, S., 2009. Road-tunnel fires: risk perception and management strategies among users. Safety Science 47, 105–114.

Hale, A.R., Glendon, A.I., 1987. Individual Behavior in the Control of Danger. Elsevier Science, Amsterdam.

Hoc, J.M., 1992. Psychologie cognitive de la planification. Presses Universitaires de Grenoble, Grenoble.

Hoc, J.M., 1996. Supervision et contrôle de processus. La cognition en situation dynamique. Presses Universitaires de Grenoble, Grenoble.

Kouabenan, D.R., Calatan, M., Gandit, M., Caroly, S., 2011. Behaviors and causal explanations of road-tunnel users during a fire. Psihologia Resurselor Umane (Psychologie des Ressources Humaines ou Human Resources Psychology) 9 (1), 69–84.

Kouabenan, D.R., Gandit, M., Caroly, S., 2006. Tunnel-fire risk perception and management strategies among users. In: Huang, P., Li, S., Zheng, C., Mao, Z. (Eds.), Progress in Safety Science and Technology, vol. VI. Science Press, Science Press USA, Inc, Beijing, pp. 901–904.

Leplat, J., 2000. L'analyse psychologique de l'activité en ergonomie. Aperçu sur son évolution, ses modèles et ses méthodes. Octarès, Toulouse.

Mintz, A., 1951. Non-adaptive group behaviour. Journal Abnormal Sociology. Psyhology 46, 150–159.

Mos, A., 2005. Modèles phénoménologiques pour la simulation d'incendies en tunnel routier. Doctoral Dissertation, Université Claude Bernard-Lyon 1.

Nuttin, J., 1979. La perspective temporelle dans le comportement humain. Etude théorique et revue de recherches. In: Fraisse, P., Halberg, F., Lejeune, H., Michon, J.A., Montenegro, J., Nuttin, J., Richelle, M. (Eds.), Du temps biologiques au temps psychologique. Presses Universitaires de France, Paris, pp. 307–363.

Orsini, F., Fraisse, P., 1959. Etudes expérimentales des conduites temporelles: la précipitation. Psychologie Française 4 (2), 117–126.

Ozel, F., 2001. Time pressure and stress as a factor during emergency egress. Safety Science 38 (2), 95–107.

Perrow, C., 1984. Normal Accidents, Living with High-Risk Technologies. Basic Books, New York.

Plat, M., Rogalski, J., 2000. Traitement des dysfonctionnements d'automatismes et modes de coopération dans le cockpit. In: Weill-Fassina, A., Hakim Benchekroun, T. (Eds.), Le travail collectif: perspectives actuelles en ergonomie. Octarès, Toulouse, pp. 135–157).

Rasmussen, J., 1986. Information Processing and Human–Machine Interaction. Elsevier Science Publishers, North Holland.

Rasmussen, J., 1993. Analysis of tasks, activities and work in the field and the laboratories. Le Travail Humain 56 (2–3), 135–155.

Rogalski, J., 2003. Y a-t-il un pilote dans la classe ? Une analyse de l'activité de l'enseignant comme gestion d'un environnement dynamique ouvert. Recherches en Didactique des Mathématiques 23 (3), 343–388.

Samurçay, R., Delsart, F., 1994. Collective activities in dynamic environment management: Functioning and efficiency. Le Travail Humain 57, 277–296.

Samurçay, J., Rogalski, J., 1993. Coopérative work and decision making in emergency management. Le Travail Humain 56 (1), 53–77.
Shield, T.J., Boyce, K., 2004. Towards developing an understanding of human behavior in fire in tunnels. In: 3rd International Symposium on Human Behavior in Fire. Belfast, UK, 1–3 September 2004, pp. 215–228.
Sime, J.D., 1999. What is environmental psychology? Text, content and context. Journal of Environmental Psychology 19, 191–206.
Sime, J.D., 1995. Crowd psychology and engineering. Safety Science 21, 1–14.
Sime, J.D., 1983. Affiliative behavior during escape to building exists. Journal of Environmental Psychology 3, 21–41.
Sime, J.D., 1985. The outcome of escape behaviour in the summerland fire: panic or affiliation? In: Pauls, J. (Ed.), Int. Conf. on Building Use and Safety Technology.. National Institute of Building Sciences, Washington, DC, pp. 81–90.
Sime, J.D., 1986. Creating places or designing spaces? Journal of Environmental Psychology 6, 49–63.
Sime, J.D., 1980. The concept of "Panic". In: Canter (Ed.), Fires and Human Behaviour. John Wiley and Sons, New York, pp. 63–82.
Soulhac, L., Perkins, R., Salizzoni, P., 2008. Flow in a street canyon for any external wind direction. Boundary-Layer Meteorology 126 (3), 365–388 (March 2008).
Spérandio, J.C., 1977. La régulation des modes opératoires en fonction de la charge de travail chez les contrôleurs de trafic aérien. Le Travail Humain 40, 249–256.
Stoetzel, J., Chandessais, C.A., 1974. Intérêt de l'étude des catastrophes pour les sciences humaines. Colloque de l'institut international du feu, centre d'études psychosociologiques des sinistres et leur prévention, table ronde du CNRS, Les comportements associés aux catastrophes, Paris, 5–6 September 1974.
Weill-Fassina, A., Benchekroun, T., 2000. Le travail collectif: perspectives actuelles en ergonomie. Octarès, Toulouse.
Weill-Fassina, A., Kouabenan, R., De la Garza, C., 2004. Analyse des accidents du travail, gestion des risques et des préventions. In: Brangier, E., Lancry, A., Louche, C. (Eds.), Les dimensions humaines du travail. Presses Universitaires de Nancy, Nancy, pp. 251–283.
Wood, G.P., 1979. Behavior under Stress: People in Fires. Doctoral Dissertation. Loughborough University of Technology, UK.
Wood, G.P., 1980. A survey of behaviour in fires. In : Canter, Fires and Human behaviour, John Wiley and sons, New York.
Wright, P., 1974. The harassed decision maker: time pressures, distractions and the use of evidence. Journal of Applied Psychology 59, 555–561.