

Human Behaviour in Tunnels

What further steps to take?

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ABSTRACT

Tunnel safety, especially in case of fires, has received a lot of attention due to heavy disasters. However, much attention is paid to controlling and extinguishing the fire, and not so much on the role of human behaviour. In this case, human behaviour includes the behaviour of road users, rail passengers, tunnel operators and emergency rescue services. Increasing the safety of tunnels starts with a proper design. The less chance of small accidents and incidents, the less chance of larger incidents or fires. Good design starts with proper lighting, signalling, enough lateral space and proper transitions from outside to inside the tunnel. In case of an accident or even a fire, In case of accidents or incidents in tunnels, the tunnel user has to understand what is going on in order to be able to show the right behavior. However, the question is whether knowing what is going on is sufficient, since people often underestimate a fire. The first period of a fire is very important, since there is no time to be lost. In case of fires, significant time can be lost from the moment the fire starts until people understand that they are in mortal danger and start of the actual the evacuation process. When this period is long, the possibility for loss of lives increases. Proper unambiguous signs should be provided (e.g. playing a fire alarm sound and specific instructions of a tunnel operator) and the same messages should be repeated via various channels. Information needs to be 'over-complete', with if possible a repetition of additional messages. Also, people with visible official status should be sent inside the tunnel to reinforce public address announcements and issue instructions to help people make the right decisions. Tunnel operators should inform the public and should stress that this is not a general message but that this is actually applying to them. Professional truck drivers should be trained to show the right behavior and stimulate others to evacuate. Many training and practice is required for operators and emergency personnel, where joint training exercises are of utmost importance.

KEYWORDS: Human behaviour, road users, tunnel design, evacuation, operator, emergency services.

INTRODUCTION

Tunnel safety has received quite some attention due to large accidents, leading to fatalities, human casualties and a lot of economic damage. In the field of tunnel safety, the human factor plays an important role. To a large extent, tunnel safety is determined by human behavior, where the probability of accidents, the severity of the accidents and their consequences depend to a great extent on the design and operation of the tunnel system as a whole.

But why do we even speak about tunnels as a separate road category? What makes driving in tunnels any different from driving on open roads? In the ideal situation, the level of traffic safety on the road should not diminish in and near tunnels. Tunnels should be designed in such a way that the level of

safety in and near tunnels is in the basis about the same as on other parts of the road network. Therefore it is important to identify the reasons for the low safety level in and near tunnels.

WHY IS A TUNNEL SO DIFFERENT?

In itself, tunnels are not crash prone but accident severity is somewhat higher in tunnels than on the national road network in general (e.g. [1], [2]). Analysis of the crash types showed that the proportions of frontal, single vehicle and other type crashes in tunnels are similar to those on road network as a whole. Rear-end collisions, however were twice as common in road tunnels as on the open roads. The distribution of tunnel and road crashes is shown in Table 1.

Table 1 Crashes in road tunnels and National roads by accident type in Norway [1].

| CRASH TYPE | INSIDE TUNNEL | ROADS OUTSIDE TUNNEL |
|----------------------|---------------|----------------------|
| Same direction | 43.3% | 22.2% |
| Opposing directions | 17.2% | 14.3% |
| Crossing and turning | 1.6% | 23.7% |
| Pedestrian involved | 1.6% | 8.1% |
| Vehicle leaving road | 29.8% | 26.3% |
| Other accident types | 6.5% | 5.4% |
| Sum of accidents | 372 | 4917 |

Crash rates decline with increasing tunnel length, which is in accordance with the fact that entrance zone crash rates are higher than those for the mid-zones. This means that especially at the transition from outside to the inside or vice versa, changes in risk occur. However, there are differences between tunnels. The crash frequencies in the entrance zones were higher for shorter than for longer tunnels. Narrow tunnels (smaller number of lanes) had higher crash rate than wider ones. It was found that there is a concentration of crashes just outside tunnel openings on roads with one-way traffic. In such cases rear-end collisions predominate. These are often related to high traffic volumes and are sometimes exacerbated by blinding sunlight and closely spaced traffic signals [1]. Besides the transitions and changes in lay-out, another major difference to driving on open roads is that if an accident happens, the consequences are far more serious in case of a tunnel compared to the open road (e.g. in case of fire and smoke). This is illustrated in Figure 1

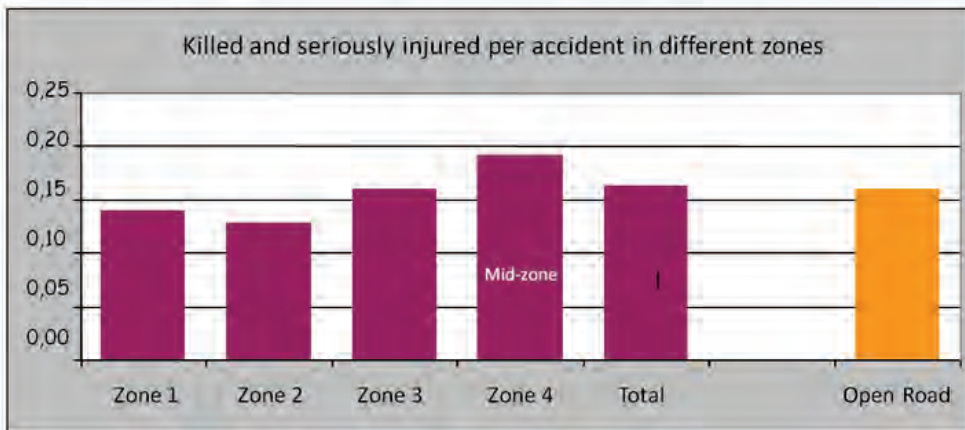


Figure 1 The number of people killed and seriously injured per accident in the different tunnel zones [3])

The purpose of this study is to identify some important human behavioral aspects related to design and organizational issues. We will focus on normal and critical situations, and we will focus on various aspects of human behavior, that is the behavior of the tunnel user, behavior of the tunnel operator and the behavior of emergency services. Each of above stakeholders has a specific role in the operation of the tunnel. These roles are interdependent. Bad coordination of these roles and mutual misunderstandings can contribute to errors and eventually to accidents.

NORMAL DRIVING CONDITIONS

Lighting

When entering a tunnel, a rather large reduction in ambient luminance may cause problems in perceiving crucial visual information inside the tunnel. Due to this limitation in perception, crucial information may be missed and dangerous situations might result. A slow adaptation process of the visual system occurs when luminance levels decrease. The eyes need some time to get adapted to the lower luminance level, and in this period of time only objects with a luminance not far below the adaptation level outside the tunnel can be perceived. When approaching a tunnel, perception is also limited due to the amount of straylight in the eye of the driver. Straylight is a constant veil that results from the light that gets scattered in the eye media, in the atmosphere and on the windshield of automobiles. This straylight forms a luminous veil that reduces the visibility of objects in the entrance of tunnels [4], [5]. This plays an important role especially at tunnel entrances, since the presence of high ambient luminance levels near a dark tunnel entrance emphasizes the relative difference and reduces the contrast of objects in the tunnel. Before entering the tunnel, the driver's fovea is adapted to the sum of the luminance of the surrounding area and the amount of straylight in the eye of the driver [6]. As a consequence, visibility problems inside a tunnel are likely to occur, unless the luminance level inside a tunnel is high enough. Due to the slow adaptation process and the presence of straylight, the luminance level inside the tunnel may appear to be extra low and, consequently, the tunnel appears as a black hole, in which no details can be perceived. Due to a lack of anticipation, the risk of rear-end collisions increases, and due to limited visual guidance, lane keeping might be difficult.

Therefore, large differences or transitions between the luminance level outside and inside a tunnel should be avoided in order to avoid adaptation and perceptibility problems. Improved lighting and tunnel entrance design have contributed positively to a significant reduction in tunnel transition zone accidents (see for an example Figure 2).

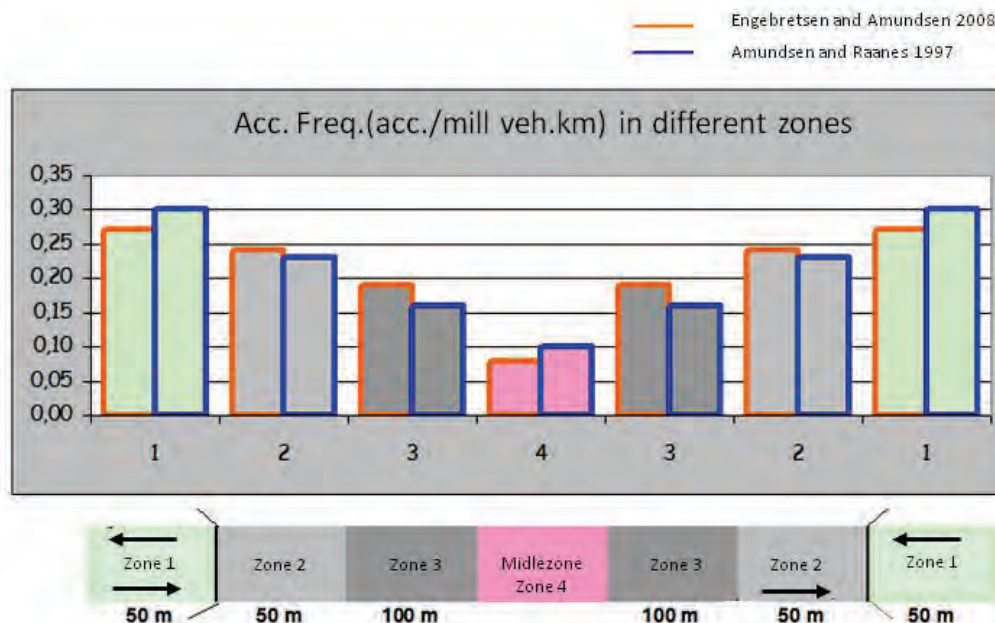


Figure 2 Accident frequency per billion vehicle kilometers travelled within the different tunnel zones [3]

Luminance differences can be minimized by increasing luminance inside and decreasing luminance outside the tunnel. Here the absolute luminance level inside the tunnel is not of utmost importance, but rather the difference between the luminance level inside and outside the tunnel and whether this

transition in luminance level is a gradual one. The luminance level inside a tunnel should allow for sufficient anticipation of objects and the road lay-out.

Proximity of tunnel wall and lateral clearance

Due to financial and technical constraints, the lateral clearance in tunnels is often minimized to a degree that is generally considered unacceptable on open roads. The proximity of the tunnel wall to the lane has an effect on perceived narrowness of the tunnel, and consequently on driving behavior.

Already decades ago, it was found that while driving on the right lane, road users drove more to the centerline marking at the beginning of the wall, where the emergency lane was interrupted. This could be an indication of fear to hit the wall with sometimes more than 30 cm change in lateral position even before the tunnel entrance. The lateral position changed again to the old position of the open road after some adaptation to the decreased available lateral space (a.o. [7], [8]). Also, steering frequency increases, indicating strenuous steering, and speed is reduced [9], [10], and [8]. A narrow tube requires better lane keeping, which is facilitated by a reduction in driving speed. On the other hand, the speed reduction can also be the result of the high amount of stimulation in the visual periphery. Research shows that too much stimulation in the visual periphery (about 30 degrees left and right of the fovea), is considered very unpleasant [11]. If the value of 2 rad/s of angular velocity is exceeded, drivers adapt their position and speed to avoid disturbing effects [12]. This speed reduction increases the risk of interruptions in the traffic flow and collisions.

In conclusion, large reductions and rather abrupt changes in lateral clearance should be avoided in order to avoid large or sudden changes in driving behavior and increase the risk of an accident. Reductions may result in increased steering activity, lateral displacement and reductions in driving speed, factors that may negatively affect driving safety since drivers may respond in different ways. In order to avoid reductions in homogeneity, and head-on and rear-end collisions, sufficient lateral manoeuvring space should be provided. A smooth transition should be provided between the standard open road, the road part approaching the tunnel and the tunnel entrance, without any sudden narrowing. Anticipation of the road lay-out seems necessary to prevent uncertainty about the available manoeuvring space and lane width should be sufficient to avoid interfering actions from passing cars and to improve the driving conditions for heavy vehicles. Although higher costs are involved, continuing the emergency lane inside a tunnel does not only guarantee a continuous amount of available lateral space, but also permits clearing the road in case of a car break-down, thereby increasing objective and subjective safety.

Tunnel length

Driving through tunnels may in itself lead to increased uncertainty and fear. This fear is partly the result of the experienced threat of getting stuck inside the tunnel in case of traffic accidents or calamities, because of experienced vulnerability and doubts on physical safety inside tunnels in these cases. Drivers mention that tunnel fear is the result of fear of hitting anything, like an object, the tunnel wall or other vehicles, and fear of problems to escape from dangerous situations, for instance in case of a fire or if a tunnel collapses. Due to this latter fear, tunnels that underpass water are considered more fearful than other tunnels, as well as longer tunnels [13], [14].

Although no objective investigations of the effect of tunnel length on driving behavior are available, one can state that extremely long tunnels should be avoided if possible. Also, information should be provided at considerable distance so that drivers can still decide to take the exit road and not enter the tunnel. In extreme cases, drivers may stop just before the tunnel entrance, leading to a large accident risk. It is also important since over-height vehicles have to stop at the tunnel portal or may enter and cause damage to the tunnel structure or system. Also, it provides a final means of forewarning the drivers of hazardous loads that there is a tunnel ahead. Providing some information about the total length of the tunnel or its remaining length may also reduce fear, since this reduces the experienced uncertainty. In some countries, information on tunnel depth is also provided, but this may also increase tunnel fear and is therefore not recommended.

Longitudinal profile

The amount of curvature in a road can have major implications for the possibility to anticipate the longitudinal profile. This applies especially to tunnels, where sight is overall more restricted than on open roads due to the presence of a tunnel tube. The tighter the curve, the more problems will occur with anticipating upcoming situations or responding to preceding traffic. Besides sight distance, tight curves will also affect the amount of effort put into the driving task. There will be more problems with lane keeping, which can either affect driving behavior directly, or indirectly by affecting driver uncertainty. Rising and falling gradients inside tunnels are also important in this respect, since they decrease the possibility to look through the tunnel, reduce sight distances, and limit anticipation. Note that also in tunnel fires, the gradients are important since they may function as a chimney. Besides this, gradients affect driving speed via characteristics of the car, with rising gradients leading to lower speeds and falling gradients to higher speeds. The combination leads to rather large variation in driving speed. Speed differences lead to reductions in traffic homogeneity and affect driving safety in that respect too. It is important to choose a speed limit that is in accordance with the driving and stopping distances, but indicating a speed limit alone does not guarantee that this is also the actual driving speed. The presence of an incident management system, that indicates when a lane cannot be used once a non-moving vehicle is detected, may to some extent make up for short viewing distances [15]. This way, auxiliary information compensates for a reduction of the anticipation distance that drivers normally need. But whenever possible, driving sight and stopping sight should be sufficient for every particular driving situation per se, without any concessions.

Road signs and signals

In general, roads have a large number of road signs to indicate destinations, bottlenecks, road numbers, rest areas, and tunnels. Sufficient information should be provided in order to let drivers reach their destination in an efficient and safe manner, although this should not lead to an overload of information. Research has shown that road users focus their attention on the tunnel entrance about 150 to 200 meters before actually entering the tunnel [16], [17]). Attention is focused on the tunnel entrance, which means that the environment in front of the tunnel should not ask for special attention. If there is too much information in the area close to the tunnel entrance, information will either not be noticed or attention, normally paid to the tunnel entrance, will be distracted. Therefore, a proper treatment of lateral areas near the tunnel is very important. It should provide a calm and comprehensible picture to drivers in order to allow them to focus their attention to the tunnel entrance. The use of road signs near tunnel entrances should be reduced to a minimum and they should not be erected immediately (150-200 m) in front of a tunnel. Besides general road signs, incident management can be used inside tunnels to inform the driver. In case of a problem, traffic may be guided and lane use can be controlled. A signal, indicating the tunnel is safe by using green arrows, would be useful in reducing drivers' anxiety. In case of closing a tunnel, there are still drivers that enter a tunnel. At the Tauern tunnel, many drivers simply passed the red lights and continued into the tunnel. A similar test was made some months later at another tunnel for a TV report and it also showed lots and lots of cars ignoring the traffic lights. Traffic lights present no physical obstacle, and also do not say why entry to the tunnel is not allowed. Without additional information, a prolonged red light may simply be taken for a malfunction, and once the first drivers ignore it, others will follow. It is important that a tunnel operator can actually physically close a tunnel.

DRIVING IN CRITICAL CONDITIONS

In the press and at conferences, much attention is being paid to large tunnel fires. After the large tunnel fires in for example Mont Blanc (1999), Tauern (1999), Kaprun (2000) and Gotthart (2001), everyone hoped that such large tunnel fires with human casualties would be history. However, large fire accidents continue and continue. To only mention some, we can mention the London Underground (2002), Burnley Tunnel Fire (2007), Channel tunnel fire (2008), and more recently Oslofjord (2011) and the M4 motorway tunnel (2011) and unfortunately many more. The interesting part here is however that the primary focus is on the fire rescue, whereas there are many stages before that offer part of the solution of fighting the problem. If we can limit the number of accidents, we can limit the chances of fire. And if we improve behavior in traffic jams, accidents or car breakdowns, we

can also limit the chance of additional accidents and fire. The first step to be taken in limiting the impact of a tunnel fire is to limit the chances of a fire, and step two is limiting the consequences of a fire.

Traffic jam

When the traffic intensity approaches the road capacity (or the network capacity) both the driving speed and the distance between vehicles decrease. Sometimes, traffic may even come to a complete standstill for some minutes. This might happen in tunnels on interurban roads as well as in urban tunnels. The risk here is twofold: On the one hand, the risk for head-tail collisions increases, and on the other hand, if traffic drives close together or even comes to a complete stop, the risk is large in case of a fire that the fire will spread quickly. Also, focussing on behaviour in traffic jams in tunnels is important since drivers who are further away from a fire may think they are in a traffic jam, since they will encounter heavy traffic (e.g. [18]). Therefore all precautions need to be taken to improve this behaviour.

One solution is to ask drivers in tunnels to maintain a larger distance between the vehicles. However practice and research have shown that this is almost impossible as well as impractical. Even though many tunnels have signs that indicate to keep a certain distance, people almost never do. In that sense people behave as they would also behave in a traffic jam outside a tunnel, and that is to drive closely together and not keep much distance in case of a standstill. Even in a driving simulator, with road users reading a specific tunnel leaflet just for entering the tunnel that indicated to keep larger distance in case of traffic jam, with road users knowing they are being monitored, drivers did not keep sufficient distance to the lead vehicle when getting in a traffic jam situations [18]. Also, in case of high speed accidents under low traffic volumes, there is hardly any sufficient distance one can keep in order to prevent additional crashes. Various traffic accidents in tunnels are recorded on video, and show that these situations are hard to avoid. The only remedy here is to have strict speed limits, to enforce these limits and to protect accidents or car breakdowns by means of traffic signals warning upcoming traffic.

Vehicle breakdown or accident

The same discussion for traffic jams also holds for breakdowns or small accidents. The absence of an emergency lane does not only affect the proximity of the tunnel wall, with an indirect effect on traffic safety as was already described, but may also have direct effects on traffic safety. In case of emergencies, such as a car breakdown, not enough room may be available to clear the driving lanes. To prevent dangerous situations, to decrease the subjective uncertainty of drivers, and to reduce fear, it is important to have enough opportunity to stop inside a tunnel and good evacuation and escape possibilities, irrespective of whether this is realised by means of an emergency lane or other facilities. Emergency lay-bys facilitate safe parking off the road, and can also be used to work on technical installations. When using emergency lay-bys instead of emergency lanes, some attention should be paid to the overview from this lay-by on the driving lanes. If a car has to leave the emergency lay-by, enough sight distance should be available to judge whether it is safe to merge into the traffic stream. In this respect, an emergency lane is much safer, since they may be used to accelerate in order to perform safer merging behavior. Also, an emergency lane offers extra space in order to avoid collisions. Many videos are available showing how an emergency lane actually helped avoid additional collisions, since drivers were able to steer to the right if the approached still-standing traffic with too high speeds. Besides providing emergency facilities for off the road parking in case of a car breakdown, a sufficient amount of evacuation facilities, for instance turning niches, should be provided for emergency evacuation of the tunnel.

Tunnel fires and evacuation

In case of an actual tunnel fire, it is very important that people behave correctly in order to limit the casualties and injuries. However, there are many studies that show that this behavior is not always the way we hoped it would be.

The Caldecott Tunnel fire (USA, 1982) killed seven people in a road tunnel, involving cargo with gasoline. This tunnel fire also started with an ordinary accident. Shortly after midnight a driver drifted out of lane and the car struck the tunnel wall. The driver brought the car to rest in the left-hand (fast) lane and got out to inspect the damage. The car was almost half-way through the tunnel. The initial accident created a bottleneck for traffic coming up behind. Probably due to the late hour of the accident and a low traffic density, other drivers did not expect a traffic jam. A double tanker carrying gasoline hit the car, and a bus behind the tanker also hit the car and/or the tanker. The bus driver was killed and the tanker driver ran downhill and made it safely out of the exit portal of the tunnel after he saw the first small fires. The natural draught in the tunnel acted as a chimney encouraging the smoke to flow uphill towards the oncoming vehicles and out of the entrance portal. The tunnel ventilation system remained off throughout the event except for a brief period when the level of carbon monoxide exceeded the trigger level. Approximately 20 vehicles entered the tunnel in the next few minutes and most drivers managed to reverse out, prompted by the smoke moving towards them. Four vehicles were trapped behind the burning tanker, some started to reverse out of the tunnel but soon left the car and walked back uphill to warn other drivers. Five minutes after the crash, one pedestrian called for help from an emergency phone but was overcome by smoke. The occupants of another truck responded too late and were also overcome by smoke close to the truck. An elderly couple remained in their vehicle and died. Some people even passed by tunnel escape doors without noticing them. In all, two people died in the initial crash(es), five were killed by the smoke and fire and two were hospitalized for smoke inhalation. All others escaped unharmed. Unknown to the people fleeing east in the tunnel there were safe passages between the two bores at intervals; these might have enabled some to escape from the fire and smoke, but none of the unlocked doors available was used.

What can we learn from human behavior here? That the guy from the gasoline truck was a hero for realizing the danger and bringing himself in safety? That he was a coward for leaving other people in their car and not helping them? Was it a stupid decision that he did not try and extinguish the fire, or was he smart not to lose valuable evacuation time by trying to extinguish a non-extinguishable fire? Were the people who walked uphill stupid since going downhill would have brought them into safety much quicker? Or were they brave in trying to warn other drivers? Was the person trying to use the emergency phone a hero or again stupid since this action eventually led to his death? It is always easy to put the blame on people afterwards, after knowing all details, but a fact is that people do what they do, since this seemed to be the best decision at that time. Installing emergency exits is simply not sufficient, and providing drivers with general information at one or several points in their driving career is also not enough. Every tunnel is different, every situation is different and every road user is different, making it difficult to educate drivers on how to behave in general.

In tunnel fires and human factors research, various stages of human response are described. The first of these has been called the interpretation stage. The ambiguity of potential disasters in their early stages, the rarity of such events and the tendency of people to interpret their surroundings in relation to the expectations of normal use, results in the initial cues being ignored or misinterpreted. People see what is going on around them and try to interpret and make sense of it. If they do not realize that there is a fire or that they need to escape, they will most likely underestimate the danger. Only after the fire is noticed, behavior enters the second stage, where people decide what to do next. Any additional information which can be given to people will make effective action more likely. If people are not convinced of the seriousness of the event, they will make the wrong decision, e.g. to wait or see what will happen next. In this stage, people have shown to greatly differ in the number of cues necessary to alert them to the likelihood that something unusual is happening. The recognition of a single cue, such as smoke, was often followed by a search for other cues before people decide what is going on in and what they should do. As emergencies are rare, such a probabilistic model is by definition likely to lead to a misinterpretation. The final stage is where people attempt to deal with the emergency, either by tackling the fire, interacting with other people, or escaping. One important aspect of this stage is that people are unlikely to produce acts under emergencies that they would or could not produce under normal circumstances. These three stages are often called the Recognition, Response and Movement times phases, with the Response stage including all actions other than movement to the exit. The Recognition and Response stages are often collectively referred to as “pre-

movement time” although this is slightly misleading as movement may not occur in the end. The movement is not directed to evacuation only, but also to other activities.

Stage 1: Recognition time

The time taken for individuals to recognize the existence of a fire is a complex function of many parameters. Some of these refer to the individual, their degree of alertness, the extent to which they are committed to their current course of action. During the process of evaluating cues, a person is very perceptive to the overt actions and communications of others, and may choose to mimic these rather than react independently [19]. Although the activities of other people are potentially important, they may also easily be misinterpreted [20]. Separated individuals respond rapidly but family groups wait until clear sign of fire threat. However, if there are many people witnessing any event they may all tend to assume that it is "someone else's problem". The information content of the cues reaching them is therefore of great significance. Whereas in buildings, a fire always starts with a fire alarm, a tunnel fire never starts with this simple and well-known signal. This is a very intriguing issue. Since this alarm is an international alarm (despite differences in sound and pattern, it is internationally recognized by many people), it will at least be a very good first step to understand what is going on. The alarm always sounds when evacuation is in place in buildings. This means that people can be warned without the need to see the fire for themselves. Adding the fire alarm may be a very valuable first step in information and alarming tunnel users and preparing them for evacuation.

Stage 2: Response time, non-egress behavior

Based upon experimental studies as well as on realistically contrived evacuation tests and exercises it has been shown that people may need up to 5 to 15 minutes to decide whether they should do anything at all and finally what to do. In this, the phase of the fire and magnitude of the fire and distance to the fire plays an important role here. Other studies of earlier stages of evacuation show typical behavior patterns characterized by uncertainty, confusion and inefficiency [21], [22]. In the Caldecott accident, the gasoline truck driver probably realized the danger from a professional viewpoint and therefore acted quickly.

The problem with fires is that one may underreact, not realizing the seriousness of the event. People are not very good at predicting the actual growth rates [23]. When the fire is small people do not feel threatened because they do not realize how fast the fire will develop. On the other hand, they may overreact. During anxiety a person's focus becomes very narrow – only allowing processing of the most obvious elements of the environment. This is confirmed by [24], who reported about actual behavior during the fires in the Mont Blanc and Tauern tunnels in 1999. The main conclusions are that people will stay in their cars as long as they do not recognize the threat of the fire. This is concluded based on the fact that in the Mont Blanc tunnel fire many victims were found inside or near their vehicles. This means that they did not start evacuating in time. In the Tauern tunnel fire, most of the people had the sense to flee on foot. Only three people stayed in their cars and died. Not to forget, a lot of people got out at an early stage, saving their life. The victims of the Gotthard tunnel fire "died because of their false appreciation of the situation and their incorrect behavior as they waited or tried to turn their vehicles, instead of proceeding immediately to emergency exits" [25]. Analyses of the Kings Cross fire in November 1997 [26] came to the conclusion that human behavior depends on the role of a person. For example a commuter who travels every day with the same goal is likely to follow the same pattern as usually even during an emergency. The Summerland fire (1977) showed that deaths were statistically most likely to occur amongst people who were in groups when first alerted. People already in groups started to move later than individuals separated from other group members, and moved more slowly as a group. At least three-quarters of the people interviewed escaped with at least one other group member. However, this may also be turned into efficient behavior if one person starts to show the right behavior, and others may follow. However, it depends on who that person is. If it is the head of a family, the family may follow. However if it is the 14 year old son, the parents may not be convinced that this is the right behavior. Therefore it is extremely important to provide different cues that all provide the same behavior and offer as much official and unambiguous cues.

A driving simulator study [18] found that even directly after reading a leaflet about what to do in various critical situations in tunnels, drivers were not very effective in applying the information. About 60% of the drivers switched off the engine spontaneously, after reading the leaflet this increased to 70%, only with the help of the operator this number rose to 100%. Not too many people used the radio to get additional information, not even after reading the leaflet (in which this was recommended). Some people wanted to use the radio but mentioned they had forgotten the frequency indicated in the leaflet. The most crucial action: getting out of the vehicle (or stating one would), was highly affected by the statement of the operator. Whereas 65% of the people indicated they would want or try to leave the vehicle, with 75% of the people who read the leaflet, this number increases to 94% after the operator announcement. So reading the leaflet already improves the situation somewhat compared to not getting any additional information. However, with the help of an operator voice, performance improves even more. This leads to more people doing the right thing, but also to getting into action more quickly. Even though participants already had passed the tunnel 3 times before and had a chance to see the exits inside the tunnel on ride 4 as well, some people still indicated wanting to use the tunnel entry to leave the tunnel. In the last group, in which it is specifically mentioned by the operator, no-one mentioned this. What was striking was that quite some people indicated they did not have an idea of how to handle the given situation (even in the condition with leaflet and operator). This means that there is a lot of uncertainty in the case of accidents or incidents in tunnels, even though there is an operator voice, and even though people read the leaflet.

Stage 3: Egress time, movement

When people finally are threatened from the fire it can be too late because of the smoke and the heat. Also, because tunnels are enclosed spaces, fires that occur result in poor visibility and the spread of smoke and toxic gases along the tunnel, the rapid development of high temperatures and a reduction in the level of oxygen in the air. Also from human behavior in fires in buildings we can learn a lot. Research has demonstrated a remarkable consistency in people's behavior during emergencies in an apparently wide variety of settings [27], [23], [28], [29]. Much effort has gone into measurements connected with the movement stage of evacuation, although it is now appreciated that this stage may not be the main determinant of the overall evacuation time.

The tendency of people to stick to the routes they know may be overcome to some extent by the provision of guidance systems (e.g. signs). Good direction signs on the other hand speed up evacuation [30]. The fact that in tunnel fires, many people try to drive or walk out of the tunnel entrance or exit, irrespective of the presence of emergency doors shows this as well. Since people know that there is open air at that entrance or exit, they prefer to choose the secure option, even allowing them to stay in their car. Reversing out of the tunnel in case that turning is not possible is also an option that is seen as safe and secure. Leaving your car and going through a door one does not know is not a very attractive option if one thing one has an alternative.

Using fire extinguishers

Even though there is a lot of debate on whether we want ordinary drivers or train passengers to try to use fire extinguishing equipment, there is at least sufficient evidence that they do not sufficiently know how to use them. On the bus in the Huegenot tunnel, the co-driver attempted to smother the flames with clothing which promptly caught fire. No one even thought of using the fire extinguisher onboard the bus, or any of those available in the tunnel, being only 50 meters away. In the Mont Blanc tunnel, the Belgian lorry driver survived, warned by the flashing headlights of oncoming vehicles, but said not to have time to use his fire extinguisher. In Tauern tunnel fire, the first extinguisher was taken out of its housing 5 minutes after the crash. Following the Taegu fire, the newspapers stated that the passengers could not do anything except panic with no one attempting to use the fire extinguishers placed under the seat. In a safety drill, following the tragic incident, it took people as long as 33 seconds to find them even if they were aware of the location. The blaze on the subway car in Taegu was raging in less than 10 seconds. Only 38% said they knew how to operate the extinguishers. In many countries, learning how to use a fire extinguisher is not part of any normal training.

Fear to leave the car

In the unpublished car simulation tests carried out for Eurotunnel, people were presented with cosmetic smoke from a car at the front of the wagon, while seated in their cars. People in the cars behind the "fire" were observed to sit and watch developments, in some cases they just closed their windows to keep the smoke out of their own car. They only evacuated the car and the wagon when they heard an instruction to do so, or saw others leaving. This corresponds to the simulated fires in two driving simulator studies for the UPTUN project [18], where drivers also closed the windows and put off the fan in order to keep the smoke out of their vehicle, and in case of trucks, truck drivers tried to pass the fire and drive out of the tunnel.

Witnesses from the Tauern tunnel reported how some drivers refused to leave their cars, despite the chaos around them. Others even tried to maneuver their vehicles in the middle of the smoky inferno and drive in the opposite direction. In the St Gotthard tunnel, it was estimated there were about 200 vehicles inside at the time of the fire. About 100 cars turned around and left the single-bore, two-lane tunnel. Once the cars were cleared, a bus full of passengers managed to reverse out of the tunnel, as did about 15 trucks. Some drivers stayed in their vehicles and tried to telephone for help. Of the 11 (eventual) fatalities, six of the bodies were found on the tarmac as people tried to reach safety, while the remaining four were in their cars. There were fewer vehicles in the Mont Blanc tunnel, but these were not able to get out. Most of the drivers, both in trucks and in passenger vehicles, stayed inside or near their vehicle. Of the 10 passenger vehicles, 4 had started to make U-turns, but were stopped practically at their point of departure. 27 of the victims were found in their own vehicle, 2 in other vehicles, and 9 elsewhere in the tunnel or refuges.

These observations receive support from a recent truck fire incident in the 7.3 km subsea tunnel in Norway on the 23rd of June 2011. A truckload of wastepaper on the lower end of the 3km long and 7% downhill slope caught fire due to engine failure. 34 people were caught downstream in the smoke. Some tried to back out in reverse their car, while others tried to turn around and drive out. Some succeeded, but some crashed with the tunnel wall and other drivers collided with other vehicles. One person was struck and injured by a car as he fumbled along the tunnel wall. Of those who left their vehicle, 7 were found huddled together in emergency phone booths, some tried to enter the cabin of a truck standing 200m from the fire, and one climbed through an inspection hatch for geologists and found refuge and fresh air in the 0.5-1m wide space between the rock face and the lining. The rest were sitting in their cars when rescued by the fire brigade just in time to avoid fatalities. Altogether, 33 people trapped in the smoke. Of the 33 people trapped in the smoke, 28 were sent to hospital with (serious) smoke damage. One of the drivers who stayed in his vehicle was rescued unharmed by the smoke. He had a new car, relatively air tight with a pollution sensor triggering automatic shift to recirculation of air in the vehicle.

Moving in smoke

The following situations illustrate that even for people who want to evacuate, this is not an easy job if too much time is lost before they come into action:

- Zarifa (Baku Metro): "It was pitch black and we couldn't see each other anymore... We groped along, somehow managing to hold onto each other and find our way out."
- Un-named lorry driver (St Gotthard): "The smoke got thicker and thicker and it got to the point where I couldn't see any more. I felt my way down from my cab pressing my hands against the wall and reached a door through which I was able to gain access to the service tunnel."
- Marco Frischnecht, Swiss lorry driver (St Gotthard): "Luckily, I drove there every day and I know where all the emergency exits are," he said. "It was dark. You couldn't see a thing, not even the lights along the edge of the tunnel. "

Large numbers of those questioned after the fire in the Zurich metro were moving through smoke from the very beginning. One person said "the air was so filled with smoke and it was so dark that I could not see the ground, or my own feet, or people standing next to me." In the Zurich fire, the smoke irritated eyes and respiratory systems almost immediately. In spite of a normal walking speed, people were exhausted after advancing only a few hundred meters. The last passengers left the tunnel roughly 20 minutes after the burning train came to a standstill. The longest escape out of the tunnel

was about 700m. The length people can move in smoke depends on the proper use of ventilation, the toxicity of the smoke (depending on the material that is burning), the temperatures, the slope of the tunnel and their physical condition. This clearly shows there are limits to self-rescue through smoke.

ROLE OF TUNNEL OPERATORS

Even though there is a lot of attention to tunnel user behavior, there is also a large role for the tunnel and train operator behavior in case of tunnel fires. The tunnel operator needs to detect incidents and accidents and communicate to the tunnel users by means of loudspeakers, the emergency phones or by activating tunnel signals and closing the tunnel.

The tunnel operator tasks are:

- Monitoring the traffic flow and situation in the tunnel (and vicinity) using cameras, sensor readings and communication equipment. A bottleneck here is that constant vigilance is required, which is a difficult job since under normal conditions not much happens.
- Preparation for effect reduction in case of accidents.
- Fast and correct detection of any event or disturbance likely to escalate into an incident.
- Closing the tunnel; switching equipment to 'emergency mode' (lights, ventilation, speed limits, escape doors, et cetera).
- Alerting other operators (where applicable), rescue services and tunnel users (instructing them for escape if necessary).
- Communicating with tunnel users to help them escape and to help them help others or correct the situation (for example: putting out a small fire).
- From the control room, assisting the rescue services in their rescue operation.
- Evaluating and registering the incident for the purpose of improvement.

In the operator task, bottlenecks may be cognitive load, education, training and experience. Since tunnel accidents and fires do not happen very often, the amount of exercise on the job is extremely limited. Therefore sufficient training and exercise with road users and rescue services is extremely important.

However, the behavior of the tunnel operator is not always perfect. The cognitive load model ([31], [32]) distinguishes three load factors that have a substantial effect on task performance and mental effort of a tunnel operator. The first factor is the percentage of available time that the operator is occupied with his or her tasks. The higher this percentage, the higher the cognitive load. The second is the level of information processing, which relates to the complexity of tasks, with experienced tasks demanding the least cognitive effort and new tasks ask the most. The third one is the number of task-set switches, which refers to the number of switches the operator has to make between different task-sets. The more switches, the higher the cognitive load.

Combination of these factors yields an indication of the operator's cognitive load, which is represented in Figure 3.

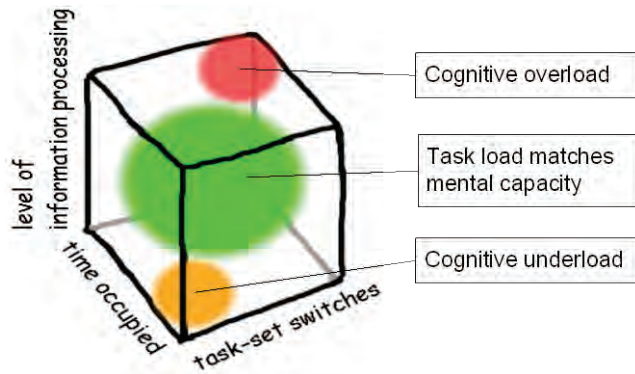


Figure 3 Schematic representation of the task load model.

Cognitive *overload* (red area) can occur when the operator does not have enough time to finish the tasks, the operator tasks are too complicated or the operator has to perform too many tasks at the same time (or a combination of any of these elements). On the other hand, if all three elements are “low”, cognitive *underload* can occur (orange area). Cognitive underload, just as overload, may lead to sub-optimal performance. Ideally, the task load matches the operator’s mental capacity in a certain task setting (green area). Other identified bottlenecks (although this list does not include all bottlenecks identified) were:

- Vigilance problems during long periods of normal operation (related to underload).
- Unclear allocation of responsibilities and authority to personnel.
- Insufficient skills due to lack of practice exercises, especially with the rescue services.
- Overdue, incorrect or incomplete detection of incident due to combination of suboptimal cognitive load and suboptimal detection of risk factors in tunnel.
- Too many incoming signals, not all of which are relevant at this time (related to overload).
- Absence of or insufficient coordinated procedures between operators and rescue services.
- Absence of adequate incident evaluating and registration procedures.
- Mistake in incident is not evaluated or registered due to fear for career consequences.

After the tasks and bottlenecks were identified, the next step was to find solutions for the most important bottlenecks and designing an improvement strategy. Using a prioritized list of bottlenecks and general methods for influencing operator behavior generates possible solutions for the most important bottlenecks. Possible solutions can be found in terms of:

- recruitment (assess the proper criteria),
- training and exercise (to improve skills, but also to test the effectivity of procedures),
- personnel and organization (number of people present, working method with time schedules and organizational culture),
- task support (such as procedures and guidelines), and
- control room and interface design (technical tools, such as one button to indicate a major accident, good tools to instruct the tunnel users).

Proper training and clear appointments of responsibility and operating procedures in case of incidents are the most crucial element of tunnel operator behavior

ROLE OF EMERGENCY SERVICES AND TRAIN OPERATOR

Directions given by people in “authority” are clearly a strong influence, as evidenced by Kings Cross (directions given by British Transport Police; London Underground staff and members of the public were not viewed as “authority” and thus were often ignored), St Gotthard (instructions to back up given by truck drivers, and later police), Zurich (directions to the portal given by the train drivers), San Francisco BART (directions from the train driver; cross-passages to the adjacent tunnel were spaced every 100m), etc.

In the Zurich metro [33], passengers on the first train were warned. Although the tone of voice from the loudspeakers seemed uncertain and nervous, the passengers heeded this advice (to wait until told to leave). Those who tried to disembark were held back by fellow passengers. Passengers on the second train remained seated, but knew that something was wrong when the conductor ran through the train declaring that there was a fire in the tunnel. There were different moods on the various exit platforms of the second train. Several people were unsure if they could have made it without presence of rescuers. It is of utmost importance to provide clear directions and instructions.

Research evidence from Kings Cross and other disasters can be used to propose certain principles to be followed in design, management and training. Information should be given rapidly, should be informative, early action should be emphasized and messages should be repeated in various forms and by various means. The need to persuade passengers to act appropriately is a key focus of emergency response; they must be provided with the maximum amount of information. Much of the delay frequently seen in evacuation is associated with people seeking confirmation before starting to act "abnormally".

One member of the Huguenot tunnel operating staff had driven into the tunnel. His vehicle was immersed in dense smoke and therefore he drove his way out again, feeling his way along the reflective studs in the centre line of the tunnel, all the time calling out to anybody still in the tunnel. Fortunately there were no people overcome by fumes lying in the road where they could be run over by his vehicle while he was doing this. (At Tauern, firefighters walked in front of their vehicle to prevent accidents like this). During the Bethnal Green incident London Underground staff, and those from the emergency services, were moving in the opposite direction and impeding the flow of passengers. This was really only a problem due to the narrow tunnel and the large number of people attempting to evacuate.

In some of the worst disasters (Baku, Kaprun, Taegu), the train doors were not opened, either because a power failure made this impossible, or the staff neglected their duty. The latter reason was suspected in Taegu, where the driver of the second train allegedly fled the scene without opening the doors, taking the master key with him, and leaving passengers trapped in their compartments. It took almost 2 minutes for a student taking part in the drill on the Seoul subway system to get out of the train by manually opening the doors. Victims of the Taegu fire would have had about 57 seconds to get the doors open before being smothered by the flames and smoke. About half of the 50 subway passengers interviewed in Seoul said they know how to operate the emergency equipment inside the trains that are used to open the doors manually.

Members of staff will usually behave in accordance with their training, but mistakes can be made. The two recovery staff who first arrived at the incident site in the Hong Kong Cross-Harbour tunnel had not fully complied with the standard emergency procedures. They did not wear smoke masks when entering the scene. They used a fire extinguisher instead of a fire hose to control the fire. One member of the staff left the scene to help with the evacuation, but should have stayed to work as a team. Both members of the staff should have stayed at the scene to hand over the operation to the fire officers on their arrival. According to the report from the rescue staff, as they did not wear smoke masks, they felt uncomfortable because of the heavy smoke and could not stay at the scene. Both staff proceeded to conduct evacuation. Failure to follow standard procedures may put the staff at risk.

The fire brigade is not immune from mistakes either. The fire brigade in the Huguenot tunnel fire scrambled immediately, but did not follow all the laid down procedures and therefore some of their operations were delayed. At Kings Cross, most fire-fighters returned to street level to collect hose and breathing apparatus; however three officers remained in the ticketing hall to supervise the evacuation of passengers. One of these three (the senior officer), Station Officer Colin Townsley, subsequently died after trying to rescue a woman passenger. At Mont Blanc, Chief Tosello of the Chamonix fire department died because there were insufficient BA kits, so he was sharing with one of his men. He had a heart attack following smoke inhalation while sheltering in a refuge with 4 other firemen.

Once rescue teams (police, firemen and medical services) are informed about tunnel accidents, they have to act in order to reduce possible consequences. By collecting data from different countries, it was possible to analysis the rescue team tasks. The main important issue in the case of rescue teams seems to be 'what needs to be done' (functions) and 'who does it' (actors).

The recent Norwegian fire disaster showed that additional measures such as rescue by ATV and IR camera greatly improves finding people and maneuvering between stranded and crashed vehicles. Also, quickly providing oxygen masks to people who escaped is very important to control the consequences.

Training and full scale exercises should always be done with all parties involved. Current training objective are often too general and evaluation sessions with rescue teams and the identified bottlenecks in the current way of training provides the opportunity to optimize training sessions. The structure of the training course should be based on the fact that the team members learn things at several levels, which they can use or apply while carrying out their job in the team.

CONCLUSIONS

The human response is a very important factor in case of tunnel accidents. As we have seen there are a lot of factors that can prevent the human being from doing the right thing. If road users do not know how to behave properly, they may wait too long in their cars. If tunnel operators are not properly selected, trained or supported they may make the wrong decision and all different parties involved from the rescue services may falsely expect the other partner to respond or may not receive the right information.

Avoiding tunnel fires starts with avoiding accidents in tunnels and limiting the consequences by a proper design, enforcing the right behavior, and using signals to inform traffic about appropriate speed limits, the closures of lanes or traffic jams. This is the first step in tunnel safety. This can be done with the proper lighting, allowing smooth transitions from outside to inside the tunnel, by avoiding sudden changes in lateral clearance of the tunnel, preferably having an emergency exit inside a tunnel, by having one-directional tunnels only, by having traffic signals above the lanes being able to dynamically control lane access and speeds.

However, in case that something happens, the tunnel user should be provided with accurate, specific and timely information. Since people underestimate the development and consequences of a fire, a lot of effort should be put into having people understand that a) there is a fire and b) it is serious and c) they need to evacuate. The first and second part can be activated by sounding a fire alarm inside a tunnel. But this is not sufficient. Information needs to be 'over-complete', with if possible a repetition of additional messages. Also, people with visible official status should be sent inside the tunnel to reinforce public address announcements and issue instructions to help people make the right decisions. Tunnel operators should inform the public and should stress that this is not a general message but that this is actually applying to them.

The presence of other people affects the individual and results in group behavior. As soon as someone reacts in a way that other people note, the behavior spreads among a group. Unfortunately, this also holds for negative behavior, such as staying in your car. It is therefore very important to stimulate the right behavior, e.g. by educating a specific group of drivers such as professional drivers (truck and bus drivers) by educating it is their responsibility to show the right behavior and instruct others to evacuate.

Critical attention should be paid to the communication procedures and facilities between the tunnel user, operator and the emergency rescue services. Only by proper co-operation can we limit the consequences of disasters. Tunnel operators and emergency rescue team members should be properly selected, trained and supported and bottlenecks should be identified in order to solve them. For rescue teams, standard operating procedures should be made and specific emphasis should be put on

knowing the responsibilities and training with all parties involved. Only by focusing on all three human groups in tunnels, tunnel safety can be improved.

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