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IMPROVING SAFETY IN ROAD TUNNELS THROUGH REAL-TIME COMMUNICATION WITH USERS

Technical Committee C.3.3 *Road Tunnels Operations*
of World Road Association

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STATEMENTS

The World Road Association (PIARC) is a nonprofit organisation established in 1909 to improve international co-operation and to foster progress in the field of roads and road transport.

The study that is the subject of this report was defined in the PIARC Strategic Plan 2012 – 2015 and approved by the Council of the World Road Association, whose members are representatives of the member national governments. The members of the Technical Committee responsible for this report were nominated by the member national governments for their special competences.

Any opinions, findings, conclusions and recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of their parent organisations or agencies.

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2016R06EN

IMPROVING SAFETY IN ROAD TUNNELS THROUGH REAL-TIME COMMUNICATION WITH USERS

The PIARC report on *Human Factors and road tunnel safety regarding users* published in 2008 (PIARC, [1]) summarises a better understanding of the behaviour of users of road tunnels. It also provides a detailed presentation of recommendations based on this understanding for the design and operation of tunnels.

This report is a logical continuation of the 2008 report and addresses specific points raised in the conclusion of that report:

- *"It is most important that motorists understand how to behave in tunnels, in ...a critical situation";*
- *"In case of fire, tunnel users should be alerted by at least two different channels of communication".*

This report deals specifically with dynamic equipment (such as signs, sirens, warning lights, etc.) that can be used to inform and warn users and encourage them to adopt appropriate behaviour in the event of incidents in the tunnel or in the approach zone. This process is referred to as "*real-time communication*". In this document "*real-time*" refers to an immediate reaction by the control centre operator based on the incident just detected. "*Communication*" refers to the link created for this specific incident between the control centre operator and the users.

This document is intended for all parties involved in the design and operation of road tunnels (owners, operators, designers, emergency services).

The report describes human behavioural aspects when driving in general, and describes how to communicate information to tunnel users in normal, congested and critical situations. It then details the various systems that could be activated in order to optimise real-time communication with users. Finally, illustrations showing how these devices can be used in cases of congestion, a serious incident and fire describe how the activation of these systems and devices must be adapted to the changing circumstances of the event. How these systems and devices interact with each other is a key component in influencing user behaviour.

The main conclusions of the report are summarised as follows:

- those wishing to implement this type of interactive approach are invited to apply the following recommendations:
  - it is of primary importance to comply with any existing national standard for the deployment of traffic signalling,
  - notwithstanding the specific regulations applicable in each country, experience has shown that a tunnel closure system is an extremely valuable safety measure in the event of a serious incident,
  - flashing exit location indicators and sound beacons at or around an emergency exit appear to provide very positive results,
  - during the evacuation phase, the sequencing of different sound and visual messages avoids ambiguity for the users;

- when these measures are applied, it is essential that information and support via training and information is provided (PIARC, [2]);
- it is also necessary, when these measures are implemented, to make tunnel managers aware of the importance of providing sufficient resources for the on-going training of operations personnel and for the maintenance of systems.

In tunnels with permanent surveillance, where the tunnel operating body is able to trigger the process, the following are also recommended:

- broadcast appropriate radio messages explaining the situation and the dangers involved and giving instructions;
- when using a tunnel closure system (closing access to the tunnel) ensure that appropriate messages are displayed on relevant variable message signs;
- when designing and implementing these facilities, it is essential that a cohesive strategy is in place for each phase of an event to ensure the activation of measures is consistent.

CONTENTS

INTRODUCTION

Improving the safety of users in road tunnels continues to be the subject of major concern as serious incidents can take place in these structures, causing injuries, deaths and considerable economic losses.

An "*incident*" is an abnormal and unplanned event (including accidents) adversely affecting tunnel operations and safety.

The definition of "*incident*" includes all kinds of events that may happen in a road tunnel. The report separates incidents into three types: congestion, minor or serious incidents excluding fire (e.g. breakdown or accident) and fire.

In this report, we have chosen to illustrate in a separate chapter the use of real-time communication systems in case of fire. The main reason is that this type of incident requires immediate and specific real-time communication actions.

From a technical perspective, a road tunnel is a "*complex system*" but it is not intrinsically dangerous. The main objective when designing and operating a road tunnel is to provide the highest possible level of safety for users, operating teams and emergency services, under all operating circumstances, with appropriate safety margins. For most tunnels, a supervisory control system (hosted in a Control Centre for significant infrastructures) is provided with three main functions as shown in *illustration 1*:

- A/**monitor any change in the current situation** (qualified as an "*incident*") thanks to various and numerous "*sensors*";
- B/ **compute the appropriate reaction** (the term "*scenario*" is often used) to the changes;
- C/ **control various items of equipment** ("*actuators*") accordingly (the control centre operator may be asked to confirm the incident or the action in certain cases).

Illustration 1- Tunnel supervision flow chart

Examples:

1. the tunnel ventilation flow rate is automatically increased if pollution is detected;
2. the tunnel lighting levels are automatically adapted to the external measured luminance;
3. barriers are closed in case of a serious incident or fire.

These three functions are continuously performed (looping from C/ to A/) and involve, depending on the specific scenario, interactions between the automated systems, the control centre operators and the tunnel users. The role of the control centre operator can be vital in this respect and should be considered as an important component of the tunnel supervision and evacuation procedures. This is however not within the scope of this report.

Tunnel users

Illustration 1 mentions three targets: road users, operating and emergency services personnel and technical equipment. The most difficult to be managed by the control centre operator is, without question, the road users, who are not predictable. Analysis of feedback from crisis situations shows two major issues:

- Actual user behaviour rarely corresponds to optimal behaviour.
- As a simple incident in a confined space such as a tunnel can rapidly become dangerous and lead to a serious incident, it is essential for the control centre operator to react as quickly as possible in order to properly influence user behaviour.

Based on this analysis, numerous experts have initiated research programs studying how human and organizational factors may be taken into consideration to improve safety for road tunnel users. These works have led to quite significant progress in knowledge of human factors. The PIARC report [1] summarizes the essential aspects of the knowledge acquired and proposes general recommendations with regard to the design and operation of the tunnel structure.

During an incident (e.g. congestion, accident or fire), tunnel users must: (1) be warned of the situation and receive appropriate information, and (2) receive relevant instructions. This can be achieved via various facilities that can be split in two main types: static or dynamic (refer to glossary at the end of this report).

Real-time communication

This report deals specifically with dynamic facilities, as they appear to be easier to adapt to developments of the incident. They can also be used to inform users and thus encourage them to adopt the appropriate behaviour according to the actual events occurring in the tunnel or in the approach zone, whatever the origin of these events: technical, traffic or, meteorological. This process (functionality) is called "*real-time communication*". "*Real-time*" refers to an immediate reaction by the control centre operator based on the incident just detected, whilst "*communication*" refers to the link created between the control centre operator and the users which is meant to deliver and possibly share information.

Static facilities are only mentioned in this report when they play an important role.

As a part of the function C/ described before, the "*real-time communication*" process (functionality) requires both a supervisory control system and the presence of a control centre operator. The former allows quick responses that are structured (by considering the consistency between the equipment and the priority/phasing of actions) and systematic, based on functional analysis elaborated by specialists during the design phase. The latter is needed because (1) a complete automation is not 100% reliable [at the time of writing this report], (2) it can be necessary to adapt the actions to the context of the incident or take into account the specific requirements of the emergency services for example.

Beyond its availability and its efficiency, the supervisory control system has one major aim and advantage: it relieves the control centre operator from stressful actions in case of critical situations and allows him to concentrate on specific tasks (for example the coordination of emergency services).

Considering that the system activation strategy is key to ensuring efficiency, the priorities proposed in *chapter 2-19, page 44* can be helpful when designing the supervisory control system. This system should be designed according to the context of the tunnel and its level of equipment which clearly facilitates the implementation of the real communication means described in this report.

Main aims

The main aims of this report compared to the 2008 report [1] are:

- to create a framework for the design and implementation of "*real-time communication*" systems taking into account, or being fully aware of, human behavioural characteristics. This framework is intended to help the control centre operator manage the incident through each phase to ensure user safety;
- to focus on the most effective facilities and best practices;
- to describe the optimal coordination of the activation of the facilities in order to warn, inform and instruct tunnel users;
- to identify new developments in facilities with "*high expectations*" in terms of safety (e.g. e-calls);
- to conclude, and, where necessary, update the previous recommendations, including on facilities for the disabled;
- to invite Owners to pay attention to cost effectiveness and priorities between facilities.

This document is intended for all parties involved in the **design and operation of road tunnels (owners, operators, designers, emergency services).**

This report addresses human factors, real-time communication systems, and provides a description of tunnel facilities.

The following topics are outside of the scope of this report:

- sensors and supervision systems that are technical "*elements*" independent of user behaviour (e.g.: anemometers, opacity detectors etc.); these elements are studied in specific reports;
- equipment that is not "*incident driven*" from a dedicated control centre, including a wide range of systems such as static equipment (studied in the previous report by PIARC [1]) and most "*in-vehicle*" systems;
- "*normal situations*", i.e. situations where all parameters are within their usual ranges or design assumptions, for example:
  – traffic flow is low enough to be fluid,
  – weather conditions are not extreme (temperature, wind, rain, fog, etc.),
  – there are no works on site e.g. nominal number of lanes,
  – technical facilities are fully available.

The recommendations presented in this report assume that the tunnels have a minimum level of equipment and a minimum level of supervision. In general, as confirmed, for instance in the EU tunnel safety directive, the tunnel manager is responsible for the safety of the tunnel. On this basis, the tunnel manager must provide users with the appropriate level of information to ensure their own safety.

In addition, educational actions and road tunnel driver training and information remain a priority (refer to previous report [2]).

Summary of previous PIARC reports dealing with communication.
Three main players are likely to be involved during an incident in a road tunnel: the control centre operator, the users and the emergency teams. The previous PIARC reports dealing with this subject are listed below:

- **Communication between users and control centre operators:** Human factors and road tunnels safety regarding users [1] and *Recommendations regarding road tunnel drivers' training and information* [2]. This report will be the 3rd one dealing with this issue.
- **Communication between control centre operators and emergency teams:** *Management of the operator-emergency teams interface in road tunnels* [3].

"Communication between users and emergency teams" could also be mentioned. This is a very specific topic which does not seem to be very relevant except in some countries depending on the: strategy, organisation, regulatory context, equipment and installation, traffic management. PIARC has not published any specific report dealing with this issue.

This report only deals with communication between control centre operators and users. Furthermore the communication processes between "*tunnel operators and emergency teams*" and "*users and emergency teams*" are outside of the scope of this report.
This report is the outcome of an interactive and interdisciplinary process with the participation of technicians, specialists from intervention teams and psychologists.

Content
Chapter 1 summarizes the main expertise put to good use in recent years concerning human factors in connection with real-time communication.

Chapter 2 presents objectives and gives a brief description of each "*Real-time communication system*".

Chapter 3 introduces illustrations of use relating to usual scenarios such as congestion, minor or serious incidents and fire.

Chapters 4 to 6 give details of the three illustrations mentioned above.

Chapter 7 presents the main conclusions.

1. ROAD USER BEHAVIOUR IN TUNNELS

The aim of this chapter is to give a brief background to some basic human factor concepts relating to road and tunnel safety and the use of Intelligent Transportation Systems (ITS). The subchapters describe human behavioural aspects of driving in general, driving in (or towards) tunnels under normal and critical circumstances, and how to communicate important information to tunnel users in these situations.

1.1. DRIVING BEHAVIOUR

Driving behaviour is one of the most complex behavioural concepts in our daily lives. Driving involves a constant process of perception and information processing, in addition to making decisions on what to do with and whether to act upon all the information reaching us (*Illustration 2*).

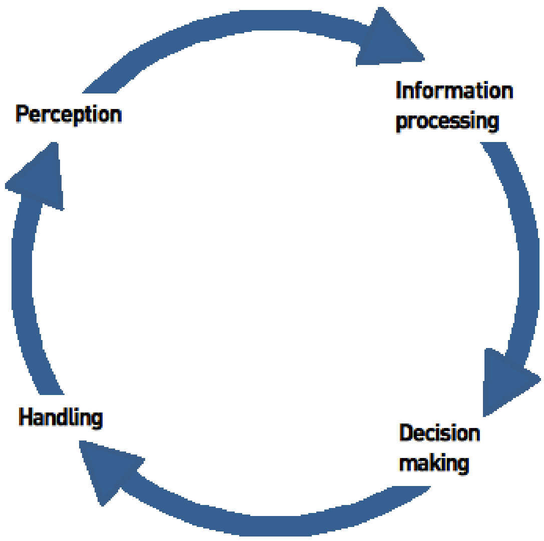

Illustration 2 - The driver behavioural cycle shows the four stages of driving behaviour

This model is a fairly simplified description of the main function of human behaviour relating to driving performance. There are many ways of exemplifying the meaning of these terms, e.g. perception is the basis for human behaviour in many situations in which our primary senses play an important role such as when we visualize and perceive the world around us. This is a crucial part of our driving performance.

The second step refers to our capacity and ability to process the information we receive from our senses and our capacity to store important information, such as in making decisions of how to drive (what speed limit did the last sign show?). The decision we make during driving can mean the difference between life and death. Therefore, it is very important that the information we receive in critical situations is as accurate as possible. Last, but not least, all of these processes will lead us to our actions or handling of the driving situation, e.g., when to slow down or increase speed, where to stop and turn etc. More illustrations of the importance of information processing are given further on in this chapter.

However, it is clear that other aspects of driver behaviour, such as intentions, attitudes, emotions and subjective norms also play an important role in modelling driver behaviour. Behaviour is not just the outcome of information processing and "*cold calculations*" on behalf of the driver, but very much the result of human intentions (some not so easy to understand) and emotional reactions such as stress and panic. This is part of our innate "*human program*" and must be taken into account as much as possible when designing future optimal solutions for tunnels. The PIARC reports [1] and [2] provide relevant information with regard to this issue.

1.2. INTERACTION BETWEEN THE USER AND THE TUNNEL

Tunnel lighting

When driving in a tunnel, road users are confronted with driving conditions that are different to those faced when driving on a regular road. When entering (or just before entering) a tunnel, a large reduction in ambient light within the tunnel reduces the visibility of the tunnel interior and can generate the perception of '*driving into a black hole*' (this phenomenon is reduced at night-time when it is dark outside). Due to this limited perception, crucial information may be missed and road users can display hesitant behaviour or reduce their driving speed suddenly, which may lead to dangerous situations. A considerable percentage of tunnel accidents take place in the zone between 50 m ahead of the tunnel entrance and 50 m past the entrance (Amundsen, Melvaer & Ranes [4]). A similar problem may be experienced at tunnel exits, when going from lower light levels inside the tunnel to higher light levels outside. But since eyes usually adapt from dark to light much faster than the other way around, the problem of low visibility leading to a potentially dangerous situation is, in general, considerably less when exiting a tunnel. A general rule that is adopted by many countries' national regulations is to gradually change the lighting levels within the first section of the tunnel (the transition zone), by using, for example, dimmers. Moreover, information should not be given in the transition area, since drivers experience a higher workload in this area which influences information processing.

Tunnel geometry

Apart from the different light conditions in most tunnels, the presence of walls and different lateral dimensions in tunnels can create the perception of different driving conditions and sometimes lead to fear in drivers. Due to this feeling of different driving conditions, drivers have a tendency to drive at a greater distance from the roadside, especially when entering a tunnel. This may cause critical interactions with other traffic in an adjacent driving lane. Field tests provided with a group of drivers in the Strahov tunnel confirmed that there is a statistically significant difference in the trajectory of a car in tunnels and on the open road. The trajectory is deviated about 30-40 centimetres to the middle of the tunnels [5]. Even when in tunnels with the same lane geometry as the open road, reductions in speed are observed when drivers enter a tunnel (Bamfylde, Porter, & Priest, [6]). Therefore, to help overcome the tendency for users to drive further away from the roadside, it is recommended to continue with a hard shoulder into the tunnel, which is also wide enough to provide an emergency lane inside the tunnel. This also allows the road to be cleared more quickly in the event of an incident, increasing objective and subjective safety ([7] [8]).

Largely because of the presence of the tunnel walls, sight is generally more restricted in tunnels. Tight curves may cause problems due to the reduced sightlines. This may require extra concentration from drivers in order to follow the course of the road. This is more apparent when lateral clearance is reduced. Increased driving effort may be experienced trying to keep in lane and when correctly anticipating upcoming traffic. In addition to tight curves, rising and falling gradients decrease sightlines and the capacity to anticipate what may lie ahead. Speed is greatly affected by gradients, especially for trucks, which may affect traffic flow and, consequently, traffic safety.

Another factor affecting driver discomfort is tunnel length. A significant number of tunnel users feel uncomfortable or anxious when driving in a tunnel (Noizet & Ricard, [9]). These negative feelings are mostly induced by the fear of hitting something (an object or the tunnel wall), or the uncertainty of where to go and what to do in case of vehicle breakdown or an emergency (Christensen, Saetre, & Beckman, [10]). These factors probably explain why longer tunnels are the source of greater anxiety for drivers; as the longer the tunnel, the longer they are exposed to these feelings of danger. However, a long tunnel can also be considered as more appealing if attractive and comfortable driving conditions are provided, such as driver-friendly road geometry and good lighting conditions.

User Information

Fear of tunnels and feelings of uncertainty whilst in a tunnel can be reduced in a number of ways. As well as taking into account the above design provisions (providing enough lateral clearance, wider curves and more gradual slope transitions), tunnel users should also be made aware that the tunnel is constantly monitored. In practice, this can simply be achieved by, for example, during ‘*normal*’ traffic conditions, showing a short item of information (e.g. traffic conditions, temperature, time, or “*tunnel under constant surveillance*”) on variable message signs.

In case of critical situations, dynamic facilities (e.g. variable message signs) may be of great value in tunnels. Since these messages can be changed, they can attract attention and provide valuable information on specific situations such as: lane closure in case of an accident; traffic lights to control traffic flow or flashing lights (flashing amber) when the road is blocked; reduced speed limits, etc. It has also been shown that a sign indicating that a tunnel is ‘*safe*’ will reduce anxiety in tunnel users, in part because this is an indication that the tunnel is being monitored (Amundsen, [11]).

Installed signs and signals must be perceived by tunnel users as providing accurate and relevant information. Perception depends on many factors, such as dimensions, lighting, colours, frequency and drive familiarity. As explained previously, in general, sight distances are reduced in tunnels and therefore extra attention should be paid to the location and the characteristics of the signs and signals. Whenever possible, the use of (international) standardized symbols and messages is highly recommended. Road users are familiar with these signs which will improve perception and understanding. Moreover the mean age of road users is increasing. In general, the elderly have weaker eyesight and more difficulties maintaining their attention and understanding signs and signals (Davidse, [12]). Therefore, it is becoming more and more important to locate and design signs in such a way that drivers have enough time to perceive the sign and prepare for and execute the appropriate actions.

1.3. ROAD USER BEHAVIOUR IN TUNNELS IN CRITICAL SITUATIONS

Behavioural processes

Since the consequences of incidents in a tunnel can be very serious and life threatening (due to the fast spreading of smoke, gases and heat), the ability for users to act independently in a critical situation is key. Human responses to risk always depend on their perception of the risk, not on an objective calculation. The problem of risk does not only concern the objective nature of the situation. It also includes different human characteristics such as an individual's belief that he/she is in control of the risk-producing activity (or can only react to it), individual risk propensity and with whom the individual compares himself/herself in relation to safety. This subjective aspect needs to be integrated in a human factors approach.

Many international reports on human behaviour in critical situations indicate that the most common reaction of people experiencing fire is disbelief of the situation and underestimation of the actual risk. People are not familiar with such situations and have a tendency to adhere to their original plans. Besides this, people are very reluctant to leave their belongings behind and often think that, in the event of a minor fire and smoke, the car is a safe place (which is not generally the case). This is especially true in the initial phase of a fire when smoke is limited and the fire is small. At this point, there are very few individuals who are willing to evacuate. Based upon experimental studies, as well as on realistically contrived evacuation tests and exercises, it has been shown that people need between 5 to 15 minutes to decide whether they should do anything at all and what they should be doing. Other studies of earlier stages of evacuation show typical behaviour patterns characterized by uncertainty, confusion and inefficiency. Moreover, people have a tendency to mimic the actions of others in crowds, especially when there is no direct perceivable reason to act and do not want to appear to '*overreact*'.

Information scenarios

People can be harmed in an accident or a fire/explosion in a tunnel. In such a situation, users have two main sources of information on which to base a correct decision as to whether to start evacuating: (1) users perceive a threat (visible smoke/fire, people leaving their vehicles etc.) and (2) some kind of warning message or signal is given by the control centre operator (auditory or text messages, etc.). Based upon this reasoning, evacuation behaviour can be described according to the following 4 scenarios (according to Kecklund et al., [13]):

1. the tunnel user perceives a threat but receives no information from the control centre operator;
2. the tunnel user perceives a threat and receives information to evacuate the tunnel;
3. the tunnel user perceives no or little threat and receives no information from the control centre operator;
4. the tunnel user perceives no or little threat but receives information to evacuate from the control centre operator.

The two sources of information on which to base decision-making can either reinforce each other, interact (as in case 2) or be ignored (as in case 4). Of course, the decision to evacuate can be based upon one source only (e.g., text message on a sign/VMS).

Real-time communication should be provided when there may be a lack of direct perception of a risk by tunnel users as well as when there is a direct perception of a risk. The real-time communication should clearly detail the safety action to be taken by tunnel users.

If the tunnel user is not directly in the vicinity of a fire or crash scene (i.e. he/she does not perceive there to be a problem), he/she has to rely upon the information given by the real-time communication systems. If the information sources are not available, the risk of a delayed evacuation is evident.

Real-time communication in critical situations

When situations are uncommon and not expected, convincing people of the seriousness of the situation can be a challenge. In such cases, different methods are necessary to alter '*normal*' behaviour. Therefore, the rule is: the more information received by the user via different means (e.g. sound beacons, light signals, operator messages), the better [14]. It is, however, important to keep information simple and concise. Specific information relating to the incident should be provided by the control centre operator. People will be informed about the incident and therefore be more inclined to relate the information to their own situation. In stressful situations it is also difficult to change ones normal pattern of behaviour due to lack of previous experience and knowledge. It is therefore vital to inform people that they are not in a normal situation. It is also important that clear instruction on what actions the users have to take is provided. Besides, it is important to suspend all regular information (variable speed limits, weather conditions outside the tunnel, etc.). This will increase the users' awareness that there is an exceptional situation and draw attention to the information. However, it is important to avoid panic, which is only likely to occur if the number of options for evacuation is limited (e.g. one passage/narrow passage) or if time for the evacuation procedure is limited. This is rarely the case in tunnel incidents requiring evacuation.

Escape routes and emergency exits have to provide a means of evacuation from a dangerous incident, such as fire, smoke or dangerous chemical spill. Signage must indicate the direction of evacuationroutes and where emergency exits can be found. Illuminated signage will assist evacuation in a smoke filled tunnel (PIARC, [15]). Emergency exits should be easy to visually differentiate from emergency stations and emergency lay-bys, this is often achieved by using different colours for different functions, and this will increase the recognition and awareness of the tunnel layout under normal and critical situations. After reaching the emergency exits, tunnel users must be directed towards a place of relative safety or ultimate safety (such as another tunnel bore or an outside area). If people hesitate, due to unclear or missing route indications, they may return to their cars. Uncertainty over the situation or the appropriate action will change perception of time. This can encourage people to return to the tunnel in the absence of clear guidance.

A basic principle for communication involves determining which of the human senses will receive information. The visual sense is clearly the most sophisticated, in terms of interpreting messages and defining colours and other complex perceptual and cognitive functions. However, the auditory sense is the most sensitive to general alarm signals (acoustic alarms) and is the most frequently used signalling means in the case of fires in buildings and on ships, etc. Acoustic alarm systems are likely to be more effective in a critical situation, whereas visual cues (messages on signs, flashing lights, etc.) can be masked by different obstacles and smoke. Therefore, in emergency situations, exits should be made more conspicuous by extra visual (flashing lights) as well as acoustical (sound beacons) signalling (Boer & Withington, [16]).

There should, of course, be no reason to choose between these two different sources of signalling as they complement each other. Other sources of communication/signalling should also be provided, such as radio messages, text messages or similar. This multi-source information principle was recommended in the previous PIARC report on human factors for tunnel users (2008, [1])

Other means of communicating

In-vehicle information systems are increasingly used by drivers. These systems can provide drivers with information on road and traffic conditions, navigation information, weather conditions, etc. Hence, these systems can improve the perception of road conditions and may decrease psychological anxiety. These systems have the potential to alleviate the demanding driving conditions in tunnels and can provide drivers with appropriate information on tunnel conditions and on critical conditions (Vashitz, Shinar & Blum, [17]). On the other hand it is known, and has been supported by empirical evidence, that in-vehicle systems (except radio) and displays can have negative consequences by distracting the attention of drivers. This may especially be the case in tunnels, in which driving conditions are even more demanding than on regular roadways. However, Vashitz et al. [17] showed that the positive effects can outweigh the negative effects, if interfaces are well designed. In addition, a recent simulator study by Rudin-Brown et al. [18] showed that driver distraction in tunnels is associated with similar reduced driving concentration on the open road when subjects read and write text messages using their mobile phones. However the authors concluded that the consequences of this reduced driver concentration in tunnels remain significantly more serious than on the open road. Such behaviour is highly dangerous and is to be forbidden during the driving task.

The focus of this report is on dynamic, real-time information. This does not, however, mean that static information cannot play an important role in an emergency situation in tunnels. For example, non-dynamic route signage or static information on tunnel characteristics can inform people in non-critical conditions, but also assist users to act appropriately in case of a critical situation. Static information can complement dynamic information by notifying people and so promote correct behaviour, in normal conditions as well as in critical ones.

Another means of influencing user behaviour is education. People are generally reluctant to act or may show inappropriate behaviour in the event of an incident or a fire; this is partly due to the fact that people are unaware of risks and of safety provisions in tunnels. Therefore, in parallel to real-time communication, it is worth educating and informing people in relation to hazards and evacuation procedures in tunnels in general. A recent study by Kinateder et al. [19] showed that behavioural training, as well as information, encourages adequate self-evacuation during critical incidents in tunnels. This was also reported in earlier work by this Working Group ([2]).

Theoretical model of time-relative egress behaviour

One way to illustrate the issues associated with the lesson learnt is the Egress time model as shown in *illustration 3, next page*. Initial feedback is based on case studies and the recollections of participants, which has led to confirmation that a model distributing the evacuation time of users was identical to the model used by Canadian researchers [20] while studying fires for individual houses.

This model illustrates the fact that contrary to belief, evacuation behaviour does not start with the fire. This model shows that it is necessary to break down the evacuation period into several steps:

- a period for detecting the event and a period for sounding the alarm,
- a period during which the user prepares for moving in the tunnel (period during which the user analyses the situation and decides what action to take),
- the period during which the user heads towards the tunnel emergency exits on foot.

As can be seen in the model below (*illustration 3*), the period during which users are on foot inside the tunnel must be shorter than the tenability limit (due to the smoke and combustion products and their movement in the tunnel). It is also clear that, during that part of the evacuation period, conditions inside the structure have already deteriorated; consequently, quick action is required to allow sufficient time for effective analysis and decision-making, and so allow for efficient and safe self-evacuation on foot.

As can be seen in the model, a number of critical time phases have been identified in a sequential order between the time the alarm is triggered and the decision to withdraw from a fire or accident area to a safe location. The model is based on feedback from building evacuations (ref. IRC), and can also be applied for tunnel evacuations. From a human factor perspective, these different phases could also be considered as more or less distinctive human response phases. In short, these phases can be labelled as 1) the perception phase, 2) the information processing phase, 3) the decision-making phase and 4) the action phase (*illustration 19, chapter 3, page 46*).

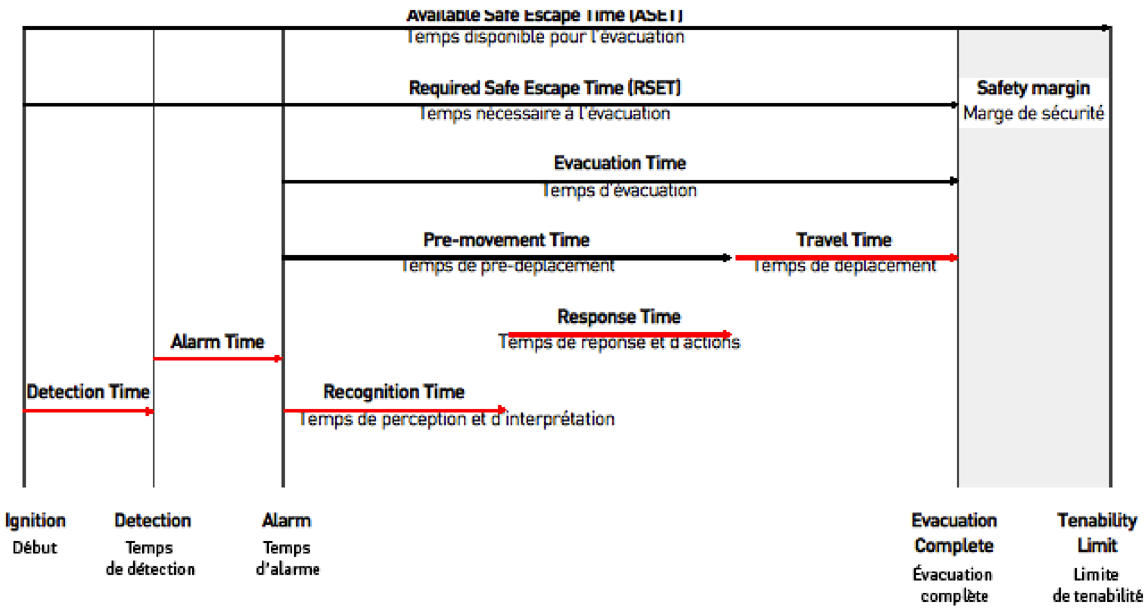

Illustration 3 - Egress time model from the Canadian Institute for Research in Construction (IRC), 2005

Definitions for the comprehension of the above *illustration 3* (according to [20]):

Detection time	The interval between the fire ignition and the 1st detection of a fire cue by a device or an individual.
Alarm time	The interval between detection of the fire and the time at which an alarm signal[1] is activated.
Pre-movement time	The interval between the time at which an alarm signal is given and the time at which the decision is made and the person starts evacuation. This consists of two components: recognition time and response time.
Recognition time	The interval between the time at which the alarm is perceived and the time at which the person interprets this signal as fire related. This time includes investigation time to determine the situation.
Response time	The interval between recognition time and the time at which the first move is made to evacuate. This time can include activities such as individual attempt of fire-fighting, warning others, gathering family members, calling for help at emergency phones, etc.
Travel time	The time needed, once movement towards a safe place has begun, for all the present people to reach that safe place.
Evacuation time	The overall time from the alarm signal to the time at which the present people reach a safe place.
Required safe Escape Time (RSET)	The calculated time necessary between ignition of a fire and the time at which all present people can reach a safe place. RSET should be shorter than ASET (below) by an acceptable Safety Margin.
Available Safe Escape Time (ASET)	The calculated time available between ignition of a fire and the time at which tenability criteria are exceeded in the means of egress.

While the escape process, where people walk to an emergency exit is deterministic in nature and consequently is easy to model, the human behaviour elements have many unknown variables ([21] – [22]). Nevertheless, this time could be significantly influenced and reduced through real-time communication with the affected people.

Research made by Frantzich and Nilsson (2004) [23] looked at different types of way-finding systems as means for influencing exit choice in an emergency. It was shown that flashing lights and sound bacons at emergency exits are systems that seem to work well under such circumstances.

Main conclusions about road user behaviour in tunnels:

- driving is a complex activity. It involves constant perception and information processing. Decisions have to be made on what to do with all the information, and actions are performed based on the information provided;
- a considerable percentage of tunnel users feel discomfort or anxiety when driving in a tunnel;
- in general, sight distances are reduced in tunnels and therefore extra attention should be paid to the location and the characteristics of signs and signals;
- based upon experimental studies, as well as on realistically contrived evacuation tests and exercises, it has been shown that people need between 5 to 15 minutes to decide whether they should do anything at all;
- road users have a lack of knowledge regarding the physical and physiological consequences of a fire in a road tunnel. Due to this lack of knowledge, road tunnel users frequently underestimate the actual risk;
- people have a tendency to mimic actions of others in crowds, especially when there is no direct perceivable reason to act. Generally people do not want to be seen to be *'overreacting'*.

[1] In the context of the tunnel: an alarm signal located inside the tunnel

1.4. LESSONS LEARNT REGARDING HUMAN BEHAVIOUR IN TUNNELS

The main lessons learnt regarding user behaviour in case of a crisis (fire) are [14] and [20]:

- feelings of anxiety and/or insecurity can be reduced by making tunnel users aware that the tunnel is constantly monitored;
- acoustic alarm systems are likely to be more effective in a critical situation than visual cues (messages on signs, flashing lights, etc.) that can be masked by different obstacles and smoke;
- road users need very direct, clear and immediate instructions concerning the appropriate behaviour in case of an event. Design of simple and intuitive safety equipment is necessary in order to have road users act upon them / use them effectively;
- importance of "*leadership effect*" (if a few users decide to self-evacuate, others will spontaneously follow);
- major need for adequate communication targeting users;
- combining resources (visual, auditory, etc.) has major benefits.

2. OBJECTIVES AND DESCRIPTION OF THE EFFECT OF EACH SYSTEM

This chapter outlines the systems likely to be activated in order to optimise real-time communication with users. The intended objectives during activation are specified for each system, and a brief description is provided. Details of the technical features are not provided. For each type of equipment, the chapter states the expected effect with regards to human factors, highlighting its limitations or added value in the situation management process.

Real-time communication systems are generally installed inside tunnels. However, in some cases it may be necessary to install them outside the tunnel due to space and other restrictions inside the tunnel (for example, where flashing lights are used in conjunction with regular signs). In these cases the recommendations provided in [1] should be taken into account. These recommendations include that "*a rather long stretch of road (if possible 150 – 200 m) before the tunnel portal should contain no signs and signals*".

Tunnel facilities include static devices, in addition to dynamic devices, which also play an important role during emergencies.

The most relevant static facilities are:

- exit distance indicators: which inform users of the distance to the two nearest emergency exits;
- tunnel user position panels: which give a reference for the actual position in the tunnel, facilitating communication with the control centre, and accelerating tunnel staff response;
- permanent reinforced lighting over emergency exits: making the exits easy to identify and improving guidance during evacuation;
- signage indicating the most appropriate behaviour such as "*Don't return to the tunnel unless instructed to do so*", "*Beware of traffic*" (when an emergency exit leads to the non-incident tunnel bore), "*Press button to talk*" and so on.

Before providing more details regarding these systems, it is important to highlight that, when activating the real-time communication systems, specific objectives depend entirely on the context of the incident. The four examples listed in *table 1, next page* illustrate that point.

TABLE 1- SPECIFIC OBJECTIVES WHEN ACTIVATING REAL-TIME COMMUNICATION SYSTEMS	
Context of the incident	**Specific objectives when activating real-time communication systems**
Traffic congestion	• Calm users, encourage them to be patient and civic minded. • Encourage users to take the incident in their stride and avoid dangerous behaviour.
Breakdown or other minor incident	• Prevent the situation deteriorating, which could lead to a serious incident (potentially followed by fire). • *With regard to users directly involved:* encourage them to pay attention to the instructions of operational staff and behave in a manner suited to the context of the incident. • *With regard to other users:* encourage them to be civic minded and avoid dangerous behaviour.
Serious incidents or accidents (with or without injured people)	• As above for "*breakdown*" objectives. • In addition, it is important to mention that inappropriate behaviour may delay the arrival of emergency and rescue teams and endanger injured users who need emergency care.
Fire with evacuation order given	• Encourage users to be aware of the situation, stop their vehicle, decide to self-evacuate, and look for the emergency exits. • Help users to locate the most appropriate emergency exits. • Encourage users to pass through the emergency exits and wait for assistance without returning to the tunnel *From the point of view of the egress model described in chapter 1, the objectives listed in bullet 1 and 2 can be formulated as: reducing recognition time and response time in order to increase the travel time available for self-evacuation.*

The following paragraphs describe the devices generally used to communicate with tunnel users. These devices are presented in the order of their frequency of use to give information or instructions to drivers. Firstly, the devices that are commonly used during any situation are described, although attention is drawn to their use during abnormal events. Then, devices which are used only when something abnormal occurs, followed by the devices used only when the order to evacuate the tunnel is given.

Real-time communications systems depend entirely on the communication network installed in the tunnel. Through these communication systems, variable instructions can be transmitted to the devices of every system required for the incident. All the systems available will be totally useless if the communications network doesn't work properly. So, close attention should be paid to protecting the ducts and the nodes of the communication network, and designing the system with the appropriate degree of redundancy, robustness and availability.

In each of the subchapters below, a table indicates the effectiveness of the system. Depending on the incident(congestion, breakdown or other minor incident, serious incident, fire), this table shows if the system is likely to be activated (yes/no) and provides general information with regards to the system effectiveness (low, medium, high) with regard to users and control centre operators' appropriate reaction.

A table provided in *chapter 2-19, page 44* summarises all these systems.

2.1. TRAFFIC LIGHTS

Objective(s)

The purpose of these devices is generally to inform users of the conditions in the tunnel ahead. Indications are generally as follows: "*free*", indicated by a green light; "*closed*", indicated by a red light; and "*restricted / be careful*", indicated by a flashing amber light. Some countries, like France, use flashing red lights when closing the tunnel. In other countries, a steady amber light is also shown jointly with the green, immediately before the transition from green to red.

Brief description

Traffic signals are mounted at each portal of the tunnel, on both sides of the approach road or close to the slow lane. They consist of two (red + amber) or three (red + amber + green) lights situated vertically. In some countries, they can also be used at regular intervals in the tunnel to provide a warning to users or to stop vehicles.

Expected effect

Drivers commonly associate green lights with an "*all clear*" message, and many countries maintain green indications continuously in normal conditions. Red lights are widely understood as an order to stop immediately. These are well obeyed, due to their frequent use on open roads. Amber flashing lights are clearly understood as a call for caution, usually making drivers drive more cautiously and making users look for further information. Hence, this device must be supported with other systems, to complete the information process.

To be used in case of:	Yes	No	Device effectiveness
• Congestion	X		high
• Breakdown or other minor incident	X		high
• Serious incident	X		high
• Fire (evacuation)	X		high

Effectiveness of this device is high in any condition, but it is more useful when showing red indications, as used in serious incidents or fire to stop vehicles, than when showing flashing amber indications.

Illustration 4a - Ville Marie tunnel (Canada)

Illustration 4b - Jihlavsky tunnel (Czech Republic)

Illustration 4 - Examples of traffic lights

2.2. LANE CONTROL SIGNALS

Objective(s)

These signals are commonly included in national regulations on traffic instructions. These signals inform tunnel users of traffic-lane availability. The following signs are used: red cross - lane closed; green arrow - lane available for traffic; and, inclined yellow (sometimes flashing) arrow - merge left or right, lane closure or obstruction ahead. These signs inform drivers that they need to change lane as their lane will close ahead, or to stop, if there is no lane available. Some countries combine these signals with flashing amber lights mounted on the same housing, to increase visibility during lane restrictions or changes in lane layout. In some countries, they can be used to force vehicles to stop, in a similar manner to a traffic light (red/yellow/green), but this is not recommended, as this information should be provided in the form of a red traffic light or other specific means of stopping vehicles (sometimes double flashing red lights).

Brief description

Lane control signals are LED light panels usually mounted centrally above each lane and showing a red cross, green arrow, or flashing inclined amber arrow. The distance between consecutive signals roughly depends on signal size, but providing visibility of two consecutive signals in the lane at any time is good practice. A red cross should always be preceded by an inclined flashing yellow arrow, or by another red cross. Care should be taken to avoid traffic congestion in the adjacent lane to which the vehicles are directed to. In the event of lane closure, it is strongly recommended that the lane closure begins and becomes completed outside the tunnel. However, a previously closed lane can be opened inside the tunnel.

In twin tube tunnels, where each tube can be used to evacuate the other tube, it is good practice to completely close the non-incident bore, to assist with the evacuation of the incident bore, while also allowing un-impeded access for the emergency services to travel to the cross-passage doors nearest to the incident. Sometimes, the non-incident bore cannot be completely closed, due to the need for the fire brigade or public emergency services to get access to the tunnel. In this case, the fast lane should be closed using lane control signals or other effective means. This will also protect pedestrians while evacuating from the incident bore.

In long tunnels, lane use restrictions should be reinforced by other means, especially when there is no immediate visible cause for the restriction, such as VMS messages, e.g. “*vehicle breakdown in slow lane*”.

Expected effect

Their use instructs motorists to change or maintain lane and can be quite effective. When used to force lane change before an incident, they are very effective to avoid subsequent incidents, and to protect tunnel personnel attending an incident.

Similar to traffic signals, green lane use indicators are associated with an “*all-clear*”, and in this case also with “*lane open to traffic*”. In these cases the signs are very effective.

When other indicators are also used drivers receive both the indication that something abnormal is occurring ahead, and the order to change lane. Consequently, their attention is temporarily increased. The reasons to close lanes should be given by VMS or, when available, by FM -DAB radio messages.

To be used in case of:	Yes	No	Device effectiveness
• Congestion	X (if necessary)		medium
• Breakdown or other minor incident	X (if necessary)		medium

To be used in case of:	Yes	No	Device effectiveness
• Serious incident	X (if necessary)		medium
• Fire (evacuation)		X	

Lane control signals are effective in avoiding subsequent incidents or accidents and to protect tunnel staff workers. Their effectiveness is medium when used in any situation, and requires additional measures to be completely obeyed and effective.

Illustration 5a - Marina Coastal Expressway tunnel (Singapore)

Illustration 5b - Valvidrera tunnel (Spain)

Illustration 5 - Examples of lane control signals

2.3. TUNNEL LIGHTING

Objective(s) of tunnel lighting during an incident

- increase the attention of drivers when approaching an incident site,
- increase the visibility of emergency exits and other safety elements near to an incident.

Brief description

Depending on the tunnel lighting design, it may be possible to set different levels of tunnel lighting for any section of the tunnel. Close to the entry portal, four or more lighting levels are normal. Further within the tunnel, there are normally two lighting levels. Levels are selected automatically in response to external sunlight, daytime/night-time, and, sometimes, traffic conditions. However, automatic lighting levels can be modified manually by the control centre operator in response to incidents. An increased lighting level will only be effective by significantly increasing the lighting level with reference to the "*normal*" level.

Expected effect

This action could be highly effective in two possible situations: (1) within the interior zone of long tunnels, when the "*normal*" level is maintained for a long distance, or (2) within the entrance zone, during hours of darkness, when the "*normal*" level of lighting is low, and a significant effect can be achieved by increasing the level.

This action can effectively increase the perception of the messages transmitted by real-time communication devices.

When used in case of a minor incident, increased lighting levels can help avoid subsequent incidents, or reduce the danger for tunnel response staff.

This option could be useful in the vicinity of an incident site with on-going evacuation, to increase the speed of travel towards the emergency exits, and to avoid subsequent incidents during the evacuation process.

To be used in case of:	Yes	No	Device effectiveness
• Congestion		X	
• Breakdown or other minor incident	X		low
• Serious incident	X		low
• Fire (evacuation)	X		medium

Effectiveness of tunnel lighting is low, but it can significantly increase safety while evacuating a tunnel.

Illustration 6a - Southern link tunnel Stockholm (Sweden)

Illustration 6b - Violay tunnel A 89 (France)

Illustration 6 - Examples of tunnel lighting

2.4. VARIABLE MESSAGE SIGNS

Objective(s)

The purpose of Variable Message Signs (VMS) is to provide users with written information and/or instructions while driving through the tunnel. Symbols/pictograms are also provided on Variable Message Sign (VMS), for example, warning indication symbols, variable speed limitations, no overtaking signs.

Brief description

VMS show one or more lines of illuminated characters mounted on a panel above the traffic lanes. The size of the characters and the number of lines of text will depend on available space inside the tunnel. If the required message is too long or too complex to display in the available space, then the full message may be split between consecutive VMS, or, the message can be shown on one single VMS in two or three alternating phrases. If possible, pictograms or symbols are preferable to letters for messages. Depending on VMS capabilities, the message displayed can be reinforced by additional flashing yellow lights, flashing the letters/words themselves, or changing the text colour, to more easily draw tunnel users' attention.

Expected effect

VMS capabilities extend to providing users with detailed information on the traffic conditions or any incident ahead. VMS are highly effective for this purpose. Most countries have rules on the communication of incidents using VMS, with standardised messages to simplify understanding. The use of pre-configured messages for all of the various situations likely to occur is strongly recommended in order to avoid any potential errors during an incident as well as to improve efficiency and ensure the right message is delivered.

Pre-configured messages are also preferable as the understanding of the message displayed will vary widely. VMS should only be used in emergency conditions to increase the attention paid to the message. However, "*White*" messages, such as time or temperature, are acceptable during '*normal*' traffic conditions. These kinds of messages may also give the impression to users that the tunnel is monitored. The VMS layouts and messages need to be carefully designed for each tunnel and tailored for all conceivable circumstances, and stored for use when appropriate.
VMS legibility is significantly reduced in the event of smoke. Therefore, their use during fire to indicate emergency exits would only be useful in areas not affected by smoke. However the legibility of the message will also depend on the size of the characters[2] [24] and [25]).

During an emergency, VMS messages can be changed in response to variable circumstances

When VMS are used to instruct tunnel users about evacuation actions, the message to be shown should be mandatory, direct and clear, including, for example, the order to evacuate.

There has been some discussion over the use of the word "*FIRE*" on variable message signs. Some tunnel operating bodies prefer the word "*EMERGENCY*" instead, as this covers a wider variety of incidents (e.g. chemical spill). However, the occurrence of a fire in a tunnel is low, and people's reaction to a fire alarm is commonly well established, leading to a more effective evacuation process. It therefore does not seem necessary to strictly avoid "*FIRE*" indications.

Some studies from Hitchins et al. [25] also state that capital letters are better than lowercase for emergency messages, but lowercase is preferable in normal situations.

Language selection is another subject to consider. The rule is to use the minimum number of languages necessary to make the message understandable, depending on the geographic position of the tunnel and the profiles of tunnel users. French regulations on the use of foreign languages, state that normal usage involves two languages plus French (CETU, [14]). However, unexpected spot announcements concerning safety or an emergency can be translated into one foreign language only, as double translation could lead to difficulties in situations where it is essential to provide information rapidly.

[2] Maximum distance for reading a message depends on the size of the characters, visual acuteness and the air transparency inside the tunnel. For a person with normal acuteness, and a good air transparency, SETRA [24] studies consider a ratio 5:1, meaning a legibility distance of 5 meters for every cm of character height. Other VMS-specific studies, for instance Hitchins et al. [25], propose ratios between 4.8:1 and 6:1.

To be used in case of:	Yes	No	Device effectiveness
• Congestion	X		high
• Breakdown or other minor incident	X		high
• Serious incident	X		high
• Fire (evacuation)	X		high

VMS are highly effective in any condition except in smoke, where there is a lack of visibility.

Illustration 7a - Hida tunnel (Japan)

Illustration 7b - Klimkovice tunnel (Czech Republic)

Illustration 7 - Examples of variable messages signs

2.5. RADIO MESSAGES (RADIO COMMUNICATION – FM OR DAB)

It is primarily important to comply with the National regulations for the relevant country. Alternatively, the EU Directive on minimum safety requirements in road tunnels [26] states, for all tunnels in the trans-European road network: “*Where there is a control centre, it must be possible to interrupt radio re-broadcasting of channels intended for tunnel users, if available, in order to give emergency messages*”.

Objective(s)

The purpose of radio messages is:

- in normal conditions, to inform tunnel users about tunnel safety systems and safe actions to be taken during emergencies;
- in case of minor incidents, e.g. breakdowns, to indicate the safe action to take;
- in case of serious incidents, toprovide information on what is happening, instruct users what to do, initiate and instruct evacuation, and direct users towards the exits.

Brief description

The radio re-broadcasting system takes selected public radio channels “*off-air*” and re-transmits them into the tunnel using a co-axial radiating cable running along the total length of the tunnel. This system allows tunnel users to continue listening to the FM (or DAB) programs whilst driving through the tunnel. When selected by the control centre operator during an incident, the public radio channels can be interrupted and replaced by pre-recorded or live information or emergency messages. A Traffic Announcement (TA) tag system must be included in the radio re-broadcasting system. This will ensure that the transmitted message will be played on the vehicle radio if the user has the TA option enabled on their radio.

Consideration should be given to developing a means of automatically remotely activating vehicle radios, setting the TA PTY flag on and transmitting on all FM, AM and DAB frequencies.

If the system integrates a Radio Data System / Traffic Message Channel (RDS/TMC), the control centre can also write a specific message which will appear on the radio screens of the vehicles, to inform or alert users.

In the case of an incident, it is very important to be able to broadcast adequate information at the right time in the tunnel. In this respect, the most efficient solution is to provide the control centre operator with the option of immediately broadcasting a pre-recorded message (superimposition of emergency messages on the retransmitted part of the FM band). However in these circumstances, care should be taken to maintain consistency and avoid any misunderstanding of the instructions. The possibility of broadcasting additional "*live*" messages, adapted to the context of the event, could be useful.

Expected effect

This system is only used to transmit messages from the control centre to vehicle radios. It cannot be used to transmit other information to emergency services or tunnel traffic officers. It is used to give information and detailed instructions to users in a clear and concise manner. A significant percentage of tunnel users will reach the decision to start evacuation in response to this kind of direct message, especially when combined with other forms of communications such as VMS and clear evacuation route markings.

Along with VMS, this system is probably the most important means of providing instructions to tunnel users. It can be used to transmit a detailed message, including evacuation instructions. This message should be as clear and short as possible, and transmitted in an authoritative tone. Minor incidents are better announced with a female voice (better understood pitch than a deep voice), but evacuation instructions are better obeyed when announced by a male voice.

Care should be taken by control centre operators transmitting live messages. There is always the possibility of misunderstanding and with some control centre operators' nervousness being conveyed in the message. This option is not usually recommended.

Language selection is also to be considered. The rule is to use the minimum number of languages necessary to make the message understandable, depending on the geographic position of the tunnel and the profiles of tunnel users.

The main effect of this system is to inform and instruct those tunnel users who have radios switched on. This actually creates a level of informed leadership. This leads to a few people starting the evacuation which is quickly taken up by those who are unsure about what action to take.

To be used in case of:	Yes	No	Device effectiveness
• Congestion	X		high
• Breakdown or other minor incident	X		high
• Serious incident	X		high
• Fire (evacuation)	X		high

The effectiveness of transmitting radio messages is high under all conditions. Its effectiveness would be strengthened in the context of information and education actions.

Illustration 8a - BPNL tunnel Lyon (France)

Illustration 8b - La Bussière tunnel A 89 (France)

Illustration 8 - Examples of radio messages

2.6. MOBILE PHONES

Objective(s)

Mobile phones can be used by tunnel users to call the emergency services in the event of an incident in the tunnel.

Other related systems include the relatively new e-Call service and a '*Broadcast-call*' service:

1 **Emergency call** (e-call). Vehicles equipped with an e-call unit will automatically transmit the vehicle's license plate number and its current geographical coordinates to public emergency services in the event of a serious collision of the vehicle. Data is transmitted using any mobile telephone network available, thus providing an early alert to emergency services and/or control centre operators. There is a European Directive (2007/46/CE and IP-11-1010) stating that all vehicles sold in the EU from 2015 must be equipped with an e-call unit.

2 **Broadcast-call.** Some mobile phone companies offer the technical option of allowing an emergency service to send out a collective emergency call to all users connected to a specific telephone cell. Messages could be in text or audio format. This option, for the purposes of road tunnels, is based on the assumption that the telephone cell only covers service users inside the tunnel. Messages from broadcast calls should be pre-recorded and give specific instructions on the situation.

Some control centre operators provide a short dial number that tunnel users can call if they need local assistance rather than an emergency service. These calls would be directed to the tunnel control centre in the same way that emergency telephones are.

Brief description

System capabilities depend on the design of the equipment providing mobile phone services inside the tunnel. Short tunnels can often be serviced from the signal outside the tunnel without any other equipment being necessary. Long tunnels require specific mobile phone cells, amplifiers and transmitting aerials or cables. The number of simultaneous calls managed by the system also limits the number of tunnel users that can receive a call, or phone anywhere simultaneously.

Full mobile phone connectivity inside the tunnel will only be available if the entire emergency evacuation route, including galleries and recesses, are serviced.

Expected effect

It is increasingly common and accepted that tunnel users use their mobile phones to alert the emergency services of an incident rather than using the roadside Emergency Telephones. It is helpful and will avoid errors and delays if the user knows their location inside the tunnel. To facilitate this, a large numeric/alphanumeric code should be provided every few meters along the tunnel walls. When a call is made using a phone in an emergency station, the caller's location is immediately known by control centre operators.

It is very difficult for the emergency services to obtain clear and complete information on the conditions in the tunnel from the user during the call. Providing the driver with instructions on how to stay safe and evacuate is more helpful than attempting to obtain information from them, as they are unlikely to have extensive knowledge of either the incident or their exact location. If a user dials an emergency phone number from their mobile phone (for example 112 for European Community, 911 for USA, 000 for Australia, 999 for UK, etc.), or an e-call alert has been raised to report an incident, the actions taken from the tunnel control centre to manage the emergency will be delayed since they may not immediately be aware of the incident. When an incident is reported by a user using a mobile phone, or an e-call alert, then the procedures for the emergency service operators must include instructions to notify the control centre operator of the incident and expect emergency services vehicles to attend the incident. This will allow the control centre operator to close a tunnel, set up lane closures, speed restrictions, etc. On the other hand, calling these numbers speeds up a response by the public emergency services.

Mobile phones are widely used by vehicle occupants inside the tunnel, but not all of them can be used easily when driving. When an alarm or instruction is transmitted to the driver's mobile phone inside the tunnel (broadcast call), written messages should also be considered. No known experiments have been carried out to test the effectiveness of this action in terms of speeding up or delaying evacuation.

Automatic e-call systems will be used in tunnel accidents, even though the exact coordinates of the vehicle are not so easily obtained using a GPS inside the tunnel. In spite of this, this system can provide an extremely early alert to emergency services. This is most valuable in tunnels without continuous surveillance or those without automatic incident detection systems (AID).

To be used in case of:	Yes	No	Device effectiveness
• Congestion		X	
• Breakdown or other minor incident	X		high

To be used in case of:	Yes	No	Device effectiveness
• Serious incident	X		high
• Fire (evacuation)	X		medium

Effectiveness of mobiles phones is high to alert emergency services and control centre operators when a serious incident occurs. However, thanks to AID and CCTV systems, the control centre operator is often already aware of the incident before the call is received. Mobile phones could be useful where there is no AID available, or in low intensity traffic conditions, when AID is not so quickly activated.

To give an early alert of a serious accident, e-call units will be very useful once the system has been widely extended. The use of a broadcast-call to give instructions to the users is not currently an option, because of technical limitations.

2.7. TUNNEL CLOSURE SYSTEMS (COORDINATED USE OF TRAFFIC LIGHTS, LANE USE SIGNAL, VMS, BARRIERS)

Objective

The primary role of a tunnel closure system is to warn tunnel users of a tunnel closure and to prevent them from entering the tunnel. Such closures may be either planned (for example in the case of maintenance works) or unplanned (in the event of an emergency such as a serious accident or a fire).

Depending on the circumstances, a tunnel closure may have one or all of the following objectives:

- prevent users from entering the tunnel,
- prevent users in the tunnel who are upstream from the incident from continuing further (in the event of an accident or fire),
- facilitate emergency service access and the evacuation of injured or trapped users.

Brief description

Barriers and red lights (flashing red lights in France and the UK), are the only specific devices used to close a tunnel. Barriers notably reinforce the dissuasive nature of red lights, but their use must not constitute an impassable obstacle and prevent the passage of emergency service vehicles. For this reason, distanced half-barriers are preferable. Because barriers are a physical obstacle they must be combined carefully with additional indicators such as flashing double red lights (as present in railroad crossings) or other appropriate means, to avoid collisions.

Other devices, such as traffic signals, variable message signs, speed restrictions and lane use signals, may also be used in addition to the use of barriers and red lights. The exact combination of the devices used will depend on the nature of the closure: planned or unplanned.

In Australia, a very specific system based on a "*Stop*" sign projected on a water curtain is also used.

Planned closures
For planned routine closures, advance warning signs and signals are to be provided well upstream from the tunnel (often in advance of an alternative route). They generally consist of a sequence of

signs and signals located at well-spaced intervals from several hundred meters before the tunnel. A complete sequence includes a series of speed reduction signals, no-overtaking signs, alternative route signs, VMS, flashing amber lights, red traffic lights, barriers and sound beacons.

Emergency closures

In the case of sudden serious incidents (rather than a planned closure, described above) there isn't usually sufficient time to display all the advanced warning messages in a timed structured manner. In these cases the need to stop more vehicles from entering the tunnel as quickly as possible is paramount and an '*Emergency Closure*' plan is implemented.
Emergency closure plans involve activating closure devices:

- at the portal,
- at the portal and inside the tunnel in the case of longer tunnels.

Closure systems at the portal normally involve activating red lights and/or flashing red lights and lowering barriers. Other advanced warning signs can also be displayed upstream when possible, for example via VMS.

Closure systems inside longer tunnels warn users who have already entered that the tube is closed further ahead and prevent approaching traffic from directly encountering the incident. In such tunnels, red lights or red crosses on the lane control signals are usually used, coupled with VMS when available. The VMS should explain the reason for the tunnel closure and indicate appropriate behaviour to users (e.g. "*Switch on radio*", "*Switch off engine*", "*Go to emergency exit*"). Amber/red traffic lights are also to be used when installed. Barriers may also be used to physically deter traffic and are usually located at the same point as the red lights and lane use/VMS signals. Barriers should use additional signals such as (flashing) red lights as previously mentioned.

All these devices should be activated from the tunnel entrance up to the incident site to discourage drivers from continuing further into the tunnel. A specific plan for their activation is necessary, to avoid confusion to the drivers ahead of the incident location.

For twin-bore tunnels with one-way traffic, both traffic directions are to be closed in the event of a serious incident. The users in the bore affected who are downstream from the incident must be allowed to leave the tunnel. Tunnel closure devices must therefore not be activated downstream from the incident. The other bore must be closed at the portal only, so as not to prevent users already inside from leaving the tunnel. This closure strategy increases safety for tunnel staff, aids evacuation of users from the incident bore, prevents subsequent incidents and usually aids access for the emergency services. Closing both bores is also sometimes necessary if smoke is re-circulating from the incident bore to the non-incident bore. Sometimes, the non-incident bore cannot be completely closed, due to the need for the fire brigade or public emergency services to access the incident bore. In this case, the fast lane should be closed using lane control signals or other effective means, to protect pedestrians while evacuating. (*chapter 2.2, page 18* Lane control signals).

In a single-bore two-way tunnel, closure devices must only stop users heading towards the incident. For each traffic direction therefore, it is important to activate only closure devices located upstream from the incident with regards to the traffic direction.

Expected effect

The effectiveness of tunnel closure systems is high. They raise users' awareness to tunnel closures and therefore directly ensure that users are conscious that the situation is not normal, either due to routine closure for maintenance or due to more serious incidents such as an accident or fire.

Closure systems are essential in terms of safety when there is a risk that maintaining the tunnel open may worsen an existing incident or create an additional incident, such as a second accident. When these systems are activated within the tunnel itself, in case of an incident which immediately requires self-evacuation by users, these systems reduce the time required for users to reach the appropriate decision, and may possibly force them to stop close to an emergency exit. However, their misuse may lead to subsequent incidents and therefore procedures for their activation must be dealt with within emergency closure plans.

Well-coordinated use of all the available devices mentioned above is therefore necessary to provide an effective means of closing a tunnel quickly and safely.

To be used in case of:	Yes	No	Device effectiveness
• Congestion	X depending on the context and normally without barriers		high
• Breakdown or other minor incident	X depending on developments		high
• Serious incident	X		high
• Fire (evacuation)	X		high

The effectiveness of a tunnel closure system is high. Its use inside the tunnel should be carefully designed to avoid subsequent incidents.

Illustration 9a - Croix Rousse Tunnel – Lyon (France)

Illustration 9b - Lioran tunnel (France)

Illustration 9 - Examples of tunnel closure systems

2.8. PUBLIC ADRESS SYSTEMS (LOUDSPEAKERS)

Objective(s)

The main purpose of a loudspeaker Public Address system inside the tunnel is to:

- provide information and appropriate instructions to tunnel users when traffic is stopped. Information about the duration of the blockage should be also included;
- provide instructions to the occupants of broken down vehicles, advising them that help is on its way, or to reach a safer place to stop the vehicle, or to leave the vehicle, as appropriate;
- instruct tunnel users to evacuate during a serious incident.

Brief description

The control centre operator can transmit live or pre-recorded messages to tunnel users through the loudspeakers fitted along the tunnel. The system design should make the messages intelligible, avoiding or minimising interference with other noise sources inside the tunnel.

Expected effect

The effectiveness of a tunnel loudspeaker Public Address system is subjective. It can be difficult to maintain the audibility of a message in a tunnel environment, especially during a serious incident inside a tunnel when ventilation fans may be running. There are specific Public Address designs for tunnels that increase the intelligibility of the messages. Use of loudspeakers is not effective with most ventilation systems and they should not be used when sirens are operating. When used to initiate evacuation, loudspeakers can transmit the emergency message alternately with a standard siren or a radio break-in message to increase the Public Address message effectiveness. This device can be also combined with sound beacons above the emergency exits (see below).

When properly designed, this system can be as effective as radio rebroadcasting, with the advantage of not being limited to vehicles with the radio activated. It can be used to transmit longer messages than VMS, including evacuation instructions.

Different languages should be used to ensure that the message is understood by the majority of prospective tunnel users. VMS considerations in relation to the use of foreign languages also apply to loudspeakers and radio rebroadcasting.

Minor incidents are better announced by a female voice (better understood pitch than a deep voice), but evacuation instructions are better obeyed when announced by a male voice in an authoritative tone.

The main effect of this system is to inform tunnel users and induce an informed leadership, able to lead evacuation appropriately, and other expected effects are: sound the alarm, provide information on the action to take and trigger action.

To be used in case of:	Yes	No	Device effectiveness
• Congestion		X	
• Breakdown or other minor incident	Occasionally	X	

To be used in case of:	Yes	No	Device effectiveness
• Serious incident	X		medium
• Fire (evacuation)	X		medium

Potential effectiveness of Public Address systems is actually limited, due to the difficulties to obtain perfect intelligibility of the messages during a serious incident, although there are some recently designed systems that considerably improve its capabilities.

Illustration 10a - Yamate tunnel (Japan)

Illustration 10b - Bell Common tunnel (UK)

Illustration 10 - Examples of public address systems

2.9. EVACUATION ROUTE LIGHTING

Objective(s)

The main purpose of evacuation route lighting is to:

- provide enough visibility for people walking along the tunnel, from their vehicles to the emergency exits, during evacuation;
- increase the rate of evacuation, thus reducing travel time;
- indicate the direction of emergency exits, and which side of the tunnel gives access to these exits.

Brief description

Evacuation route lighting consists of light sources located along the tunnel wall, providing enough light for the people walking along the marked route to the emergency exits. These lights are usually only switched on in the event of an incident. These light sources are usually fitted at a low height and are directed towards the walkway or the hard shoulder.

Some tunnels combine evacuation route lighting with marker lights, which are also fitted on sidewalls. Evacuation route lighting should not be confused with marker lights, which are permanently lit, and are also intended to guide users evacuating the tunnel on foot in the event of emergency. In addition, these marker lights indicate the lateral limits of the road and improve guidance for road drivers. In Spain, for example, some tunnels are equipped with marker lights and evacuation route lighting which are intended to improve the evacuation process.

Expected effect

Evacuation route lighting provides a visual reference line along the tunnel. It does not trigger an evacuation, but greatly speeds up the rate of evacuation because it provides intuitive guidance. Information about distance to the closest exits must be added in both directions in the form of static signs on side walls. The two facilities complement each other during evacuation: evacuation route lighting marks a route to follow, and provides enough light for safe walking; and static signs along this route confirm the route and indicate the distance to a safe place.

To be used in case of:	Yes	No	Device effectiveness
• Congestion		X	
• Breakdown or other minor incident		X	
• Serious incident	Evacuation only	X	
• Fire (evacuation)	X		high

The effectiveness of evacuation route lighting is high, as its meaning is intuitive and needs no other device to obtain effective guidance. When an evacuation order is given, marker lights fitted on the other side of the tunnel (if no exit facility is available) should be switched off to avoid confusion for evacuees.

Illustration 11a - Bracons tunnel (Spain)

Illustration 11b - Tunnel in Switzerland

Illustration 11 - Example of evacuation route lighting

2.10. EMERGENCY PHONES

Objective(s)

The main purpose of emergency phones is to:

- enable communication between the control centre and tunnel users;
- enable communication between pedestrians in emergency refuges and the control centre.

Brief description

Emergency phones are essentially the same as an intercom or telephone, connecting directly to a control centre operator, and usually without a keypad. Many systems use hands-free communication, activated when pushing the intercom button. A pre-recorded message can then be heard, informing the caller that the call will be attended to. Live bi-directional communication will then be established with the control centre operator. Some systems include two or more different buttons, to be used depending on the kind of incident: breakdown, accident or medical request. However, experience has shown that most users push all of the buttons to speed up the response. Sometimes, emergency pushbuttons are located between consecutive emergency phones. These manual call points are similar to fire break-glass units, and are marked "*Press for SOS*". Their only purpose is to provide the operator with the location of the incident within the tunnel, without providing any voice communication.

Expected effect

Regularly spaced emergency phones inside tunnels are frequently used to report incidents. When an emergency lay-by area is provided and clearly marked, an emergency telephone should be located and illuminated within this area. This system layout is used to raise the initial alarm in a significant percentage of incidents[3] (TABASA [27] and [28]).

Emergency phones can speed up the incident response, they are used to provide the necessary details of the non- serious incident (user name, license plate, insurance numbers, etc.), and to give instructions to tunnel users. However, in cases of serious incidents or fires, it is very difficult to obtain much useful information from users over the telephone. For these incidents the action taken from the control centre is usually based on information received from other sources, mainly the CCTV system, and tunnel condition sensors (opacity, CO, temperature, traffic intensity and speed, etc.).

When emergency phones are situated in a safe and protected place, beyond the emergency exit, or along the evacuation route, this communication option can be used to give instructions to users while they are following the evacuation route or waiting to be evacuated. In this respect, some emergency phones should be located along the evacuation route.

To be used in case of:	Yes	No	Device effectiveness
• Congestion		X	
• Breakdown or other minor incident	X		high
• Serious incident	X		high
• Fire (evacuation)	X		high

The effectiveness of emergency phones is high when a user is reporting incident details to the control centre operator and for the control centre operator to provide appropriate instruction to tunnel users, but it's usually not the best option during serious incidents or fires.

[3] Incidents, accidents and fires at Vallvidrera tunnels, 1991 to 2011 (TABASA). Incidents, accidents and fires at Bracons tunnels (TABASA 2010 to 2011)

Illustration 12a - Torrnkogsstunnel north Stockholm (Sweden)

Illustration 12b - Cadi tunnel (Spain)

Illustration 12 - Examples of emergency phones

2.11. FLASHING EXIT ROUTE INDICATORS

Objective(s)

The main purpose of flashing exit route indicators is to:

- increase the visibility of the exit door location when a user is moving towards the door;
- speed up the rate of evacuation, thus reducing travel time;
- indicate the direction of emergency exits, and which side of the tunnel gives access to these exits.

Brief description

In some countries, flashing exit route indicators consist of a strip of little white or green illuminated arrows or spotlights mounted along the tunnel wall, on both sides of the emergency exit door. Other countries use very big illuminated chevrons on both sides of the exit, in its immediate vicinity. In case of evacuation, these green arrows light up alternately, creating the illusion of a moving light pointing towards the exit. They light up during evacuation, and lead to the door from both sides of the tunnel, creating a visible sign that apparently moves in the direction of the exit. They are generally visible only in the vicinity of the exit.

Further investigation and tests are still required, before deciding on the most effective design and installation for these types of indicators.

Expected effect

This system indicates the direction to take along the tunnel in the immediate vicinity of evacuation exits, increasing the possibility of reaching the appropriate exit. This device can be combined with other indications to trigger evacuation, acting as a means of secondary confirmation.

To be used in case of:	Yes	No	Device effectiveness
• Congestion		X	
• Breakdown or other minor incident		X	

To be used in case of:	Yes	No	Device effectiveness
• Serious incident		X	
• Fire (evacuation)	X		low / medium (depending on the design)

Various kinds of systems are implemented in different countries. The effectiveness of flashing exit route indicators is low or medium depending of the overall system design.

Illustration 13a - Bois de peu tunnel (France)

Illustration 13b - Les Dos Valires tunnel (Andorra)

Illustration 13 - Examples of flashing exit route indicators

2.12. FLASHING EXIT LOCATION INDICATORS

Objective(s)

The purpose of flashing exit location indicators is to provide visual information on changes in the situation and allow users to identify the location of emergency exits.

For tunnel users following the indications, they also provide guidance on the best safe way to evacuate the tunnel.

Brief description

This device consists of a set of flashing lights, which are activated during evacuation on each side of the emergency exit. The exit itself is also frequently marked out with permanent lights that enhance light levels at the door and in the surrounding area, providing static facilities to help locate the exit.

In France, this device consists of two light bars located on either side of the exit. Each of these two bars includes three flashing white lights.

Expected effect

This device can help to locate the exits. Tests carried out in the Moulin tunnel [14] showed that flashing lights are the best signalling element in terms of perception in a smoke-filled environment, and effectively help and encourage users to locate and pass through the emergency exits.

As this device is intended to attract tunnel users to a safe exit, white lights are better than yellow or amber lights, due to the general association of flashing coloured lights with a "*warning -*

danger" signal. White flashes are also quite visible in a smoke-filled environment. Studies carried out by Lund University 2014 [29] recommend that the colour of flashing lights should be either green or white, whereas blue lights are not recommended. Flashing rate is recommended to be between 1 Hz and 4 Hz. The layout and position for the flashing lights can be either with one or three lights, or two bars on the side of the door.

The overall effect of these signals is to indicate the location of the exit door, and provide guidance along the way to this door. When the decision to evacuate is taken, tunnel users will search for their appropriate exit. Exit indications should be visible at all points in the tunnel, and in all conditions, regardless of visibility. Evacuation lighting, when appropriately sited and with the adequate intensity, can provide excellent guidance, and help to avoid route obstacles. Static exit distance indicators positioned along the route to the exit confirm that this is the right route and distance to the emergency exit. These indicators will be reinforced in the vicinity of the exit, with the flashing exit route indicators (chevrons), flashing exit location indicators and sound beacons above the doors.

To be used in case of:	Yes	No	Device effectiveness
• Congestion		X	
• Breakdown or other minor incident		X	
• Serious incident	Evacuation only	X	
• Fire (evacuation)	X		high

Although effectiveness can be limited in smoke, flashing exit location indicators have a high performance rate in case of fire.

Illustration 14a - Parc des Princes tunnel (France)

Illustration 14b - Cadi tunnel (flashing exit location indicators combined with flashing exit route indicators)

Illustration 14 - Examples of flashing exit location indicators

2.13. SIRENS

Objective(s)

The purpose of these devices is to make users aware that a situation has changed and is now critical and that they are in danger. In addition, sirens can encourage users to get out of their vehicles. These devices are used in traditional fire alarm systems and people are aware that when hearing a fire alarm siren they should evacuate.

Brief description

Sirens consist of specific loudspeakers broadcasting a fire alarm in the tunnel. This fire alarm does not indicate a specific message and is only a sound. Typical sounds include alternating tones and short blasts.

Expected effect

An experiment in the Moulin Tunnel (A86 – France) [14] confirmed that users do not immediately leave their vehicles when the sirens sound. Instead, they look around, detect that the situation is becoming dangerous, and realise the danger to themselves. Witnesses of the experiment say that the signal is clearly perceived as an indication of danger or a problem inside the tunnel, which makes users look around and decide what to do. Sirens alert users and ensure that they are ready to take action.

This device can be combined with loudspeakers and a public address system, and transmit a standard alert sound and the emergency message sequentially, to increase effectiveness. If the two systems are not integrated, they will not be compatible, as sirens cannot emit intelligible loudspeaker messages.

A project, known as POLLICINO, in which St. Gothard tunnel staff is participating, involves the development of a prototype sound beacon that can indicate direction, aiming to lead tunnel users in the right direction without visibility. The system combines sound beacon sequences, which are themselves activated sequentially in order to indicate the right direction.

To be used in case of:	Yes	No	Device effectiveness
• Congestion		X	
• Breakdown or other minor incident		X	
• Serious incident	Evacuation only	X	
• Fire (evacuation)	X		medium

Sirens are very effective at improving the awareness of users at the beginning of the evacuation process. However, in terms of getting an immediate evacuation, their effectiveness seems to be medium. It can be useful to combine them with other systems (public address systems, etc.) to provide information to users with regard to appropriate reaction.

2.14. SOUND BEACONS ABOVE EMERGENCY EXITS

Objective(s)

The purpose of sound beacon systems is to:

- sound a general alarm for users in the absence of a siren;
- confirm the alarm after the signal given by the siren by providing clear information and instructions to users;

- assist users to locate the emergency exits in a smoke-filled environment;
- encourage users to reach and pass through the exit.

Brief description

This device consists of sound beacons installed at each emergency exit, directly above the doors and in both directions in the tunnel. The recommended message in this context is "*Attention – Danger – Exit here*".

When selecting which languages to use, the best rule is to use the minimum number of languages necessary to make the message understandable, depending on the geographic position of the tunnel and the profiles of tunnel users.

Expected effect

After activation, this device is expected to have the following effects:

- shorter period required for perception, interpretation and analysis by users;
- shorter response time for the decision to take action;
- more time available for users to reach the entrance of an emergency exit;
- consequently, increased safety margin.

With regard to these expected effects, messages such as "*Exit here*" are clearly understandable and unambiguous.

Studies carried out in the Moulin Tunnel (A86, France) and reported by CETU [14], showed that users near to emergency exits leave their vehicles spontaneously after hearing and understanding the sound beacon messages. Users further away from the exits and the sound beacon messages are alerted by other users leaving their vehicles, and follow the others, now considered as "*leaders*".

To be used in case of:	Yes	No	Device effectiveness
• Congestion		X	
• Breakdown or other minor incident		X	
• Serious incident	Evacuation only	X	
• Fire (evacuation)	X		medium

There is insufficient evidence of the actual effectiveness of sound beacons, although it's likely to be medium or high, depending on the context. Tests carried out in public buildings and stadia report excellent results in evacuation.

Illustration 15a - Cadi tunnel (Spain)

Illustration 15b - Noord tunel (The Netherlands)

Illustration 15 - Examples of sound beacons above emergency exits

2.15. VIDEOPHONES

Objective(s)

The purpose of videophones is to provide tunnel users with a means of communication to the control centre operator once they have reached a safe place. A safe place may be a cross connection passage between tunnel tubes, an emergency gallery or shelters with an escape route separated from the tunnel tube. Audio and video communication with the control centre operator usually calms users, makes them feel more confident and trust the system. On the other side of the system, images of the users could assist the control centre substantially in assessing the situation, and provide more precise information than voice communications alone, which can be confusing or misunderstood.

Brief description

Videophones are usually fitted in a safe place, along or at the beginning of the emergency escape route and in the control centre. They consist of a CCTV camera and monitor and a telephone or intercom. These devices are available to users during the evacuation process. Control centre operators can see and hear users, and vice-versa.

Expected effect

This system is usually only used to provide tunnel users with further information after they have reached a safe place during a tunnel evacuation. The system will boost confidence and increase the patience of users during their wait to be evacuated, or if they are required to follow instructions during the evacuation process. A live view of the users can help the control centre operator to define or adapt the evacuation plan.

When using this system, users should get the impression that the situation is under control and all negative messages should be avoided when images of the control centre are shown.

To be used in case of:	Yes	No	Device effectiveness
• Congestion		X	
• Breakdown or other minor incident		X	
• Serious incident	X		high
• Fire (evacuation)	X		high

Effectiveness of videophones is quite similar to emergency phones, being rated high both in serious incidents or fire situations.

Illustration 16 - Example of videophones, Mont Blanc tunnel (France – Italie)

2.16. PUBLIC ADRESS SYSTEMS IN EMERGENCY GALLERIES OR REFUGES

Objective(s)

As an alternative to videophones, loudspeakers can be fitted in shelters, or along the evacuation route. Their purpose is to instruct users on what action to take to ensure a safe evacuation (remain calm, do not return to the vehicles, help disabled users, stay in a safe place once reached, time to rescue, etc.).

Brief description

This system is usually fitted in a safe place, along or at the beginning of the emergency route. It consists of loudspeakers which are available to users during the evacuation process. Messages can be pre-recorded, or transmitted live from the control centre. When using this system, the control centre operators can be heard by users, but users cannot be seen (or heard) by the control centre operators, unless there are CCTV cameras in these locations.

Expected effect

When fitted in shelters or along the evacuation route, loudspeakers are easier to understand and can be very helpful if the information provided is relevant to the actual situation. Clear instructions, not subject to interpretation, and pronounced in an authoritative tone, are recommended. Combining this system with emergency phones or videophones is recommended to improve communication and allow users to confirm their needs.

To be used in case of:	Yes	No	Device effectiveness
• Congestion		X	
• Breakdown or other minor incident		X	
• Serious incident	Evacuation only	X	
• Fire (evacuation)	During evacuation		medium

This device has the same limitations as public address systems, although its intelligibility is usually better due to lower ambient noise in emergency galleries or refuges.

Illustration 17a - Les Dos Valires tunnel (Andorra)

Illustration 17b - Tunnel A 89 (France)

Illustration 17 - Examples of public address systems in emergency galleries or refuges

2.17. DIRECTION SIGNS IN CROSS CONNECTIONS

Objective(s)

In cross-connected twin tube tunnels, where one tube is part of the evacuation route for the other tube, the evacuation route from the incident bore to the safe bore passes through the cross-connection passage. While passing through these galleries, users should be informed about the safe evacuation route, instructed not to return to the incident bore or to their vehicles. These instructions must ideally be dynamic, because cross-connections can be used in both directions, according to circumstances.

The main purpose of evacuation instructions in cross connections are:

- to indicate to evacuees the appropriate direction to take on the evacuation route;
- to warn of inappropriate behaviour, to warn against returning to the unsafe tunnel, or the vehicles.

Brief description

This device consists of variable message signs, fitted on the ceiling or on the wall of the crossing gallery. According to the circumstances, the message will indicate the direction of evacuation, including a green arrow and written text such as "*EXIT DIRECTION*".

Expected effect

The position of these devices must be clearly visible to all people arriving at a cross passage. If height is adequate, an elevated position over the appropriate exit door is preferable to wall-mounting.

In twin tube tunnels, where each tube can be used to evacuate the other tube, it could be necessary to completely close the non-incident bore to traffic, to assist with the evacuation of the incident bore. Sometimes, the non-incident bore cannot be completely closed, due to the need for the fire brigade or public emergency services to access the incident bore. In this case, the fast lane should be closed using lane control signals or other effective means, to protect pedestrians while evacuating (*chapter 2.2, page 18* Lane control signals).

Under all circumstances, users walking in cross passages must be informed that they are about to enter a road tunnel, and encouraged to pay attention to traffic. This information must be provided using static devices such as signage on the door leading to the safe tube or via loudspeakers.

An additional message should be displayed on the other exit door to prevent people from returning to the unsafe tunnel. According to the Vienna Convention, an R-101 "*no entry*" sign is the best option. A variable message can also be used, placed on the symmetric panel over the exit door in the wrong direction.

To be used in case of:	Yes	No	Device effectiveness
• Congestion		X	
• Breakdown or other minor incident		X	
• Serious incident	Evacuation only	X	
• Fire (evacuation)	X		medium

Various kinds of systems are implemented in different countries. The effectiveness of direction signs in cross connections are still to be evaluated.

Illustration 18a - Westerscheldetunnel tunnel cross connections (The Netherlands)

Illustration 18b - Talant tunnel (France)

Illustration 18 - Examples of dynamic signs in emergency galleries or refuges

2.18. "IN-VEHICLE" SYSTEMS

Technological developments are progressing rapidly, and systems currently exist that can potentially improve safety. Some of these systems can prevent accidents or alert drivers to the need to take action in the event of a dangerous traffic situation, and some systems can increase safety in the context of a serious incident or a fire in the tunnel.

Some of these systems are already in use, although most of them are only an option in luxury vehicles. Others are still only in the development stage.

In this section, new or future systems are described that can improve safety or accelerate appropriate actions in an emergency situation. The expected effects of these systems, and information on their future applications in relation to the objectives of this report, are outlined.

Global Positioning System (GPS)

This system belongs to the category of in-vehicle systems and is now widely used. Geolocation systems are now widely available, and can detect the exact position of vehicles inside a tunnel, and show their positions on a map. This option can help users to find emergency exits and other safety devices.

Although full GPS functions are not available inside tunnels, as a minimum of three GPS satellites must be visible in the sky to obtain an exact position, in-vehicle built-in navigation systems using GPS, also include an odometer, gyroscope and a set of sensors which can be used to estimate the vehicle's position within the tunnel quite accurately. In addition, these systems use digital maps and Map Matching Algorithms, and a position can be determined on the map quite precisely even if no GPS signal is available.

GPS map accuracy is improving rapidly. Despite this, only a few emergency routes or exits are currently mapped by main mapping sources.

GPS users can obtain valuable information from the map display. They can save substantial amounts of time, and increase the effectiveness of the action taken while proceeding to emergency exits during an evacuation.

When combined with a radio or telephone, used to transmit current position coordinates, GPS can be used to position emergency service units during rescue operations. This system is used widely outside of tunnels, to position units or vehicles. However, the appropriate devices must be fitted in the vehicle for this purpose. The results can be displayed on a map with great precision (a few meters).

Instantaneous messages

Social networks are now part of our lives. These systems, that combine high level mobile telephones with internet use (smart phones), can also potentially be of use in emergency conditions. Some infrastructure managers, and most traffic police teams, are active on networks, and transmit messages on traffic conditions, accidents and diversions. The same channel could be used to warn tunnel users when an abnormal incident occurs. Messages can be sent as text or in audio format, and can include instructions. To receive the messages transmitted by any specific information supplier, it is necessary to "*follow*" the supplier and, on this basis, the number of tunnel drivers that will be informed will depend on the popularity of the supplier. There is no current system able to transmit to all smart phones inside a tunnel using a social network, although this is a real option via text messages or call-broadcasting (see paragraph on mobile phones). Should this system actually become viable, it would have the same expected effects.

Co-operative systems

This family of systems manages early warnings and information transmitted directly from the infrastructure to vehicles (I2V), to provide early warnings or information. This system has great potential, and is supported by European Mandate M/453, but is still in the prototype stage of development. The full system requires on-board equipment to display information to users, normally combined with a radio unit, or the vehicle control panel, and a channel used to transmit the information from the tunnel manager to the vehicles.

Vehicle to vehicle (V2V) systems are related to this family. This category of equipment does not require communication with the infrastructure. Despite this, each individual vehicle can detect abnormal situations (slow traffic, congestion, fog, snow, slippery pavement, rain, etc.), and can dynamically alert vehicles that will arrive at that section of the road. This system has great potential, but is outside of the scope of this report.

Automatic driving systems

As yet, no viable automatic driving system is available. However, many partial initiatives are heading towards this objective. When this system becomes reality, communication with the infrastructure will be necessary, to obtain data on traffic limits, lane changes, etc. Traffic safety will be the main objective, and tunnel driving characteristics should be integrated in the system.

2.19. SUMMARY

The device effectiveness is indicated, using different shaded patterns, the colour codes as indicated in *table 2*.

Table 3 below provides a summary of the proposed use and effectiveness of real-time communication resources in terms of communication with tunnel users. This table is a compendium of the proposals included in the text for the different devices. Although normal situations are not covered by the text, the principles for the activation of the systems in this particular tunnel status are also included in the table. The relevant comments are provided in order to clarify the various uses of the real-time communication resources depending on incident status.

TABLE 2 - COLOUR CODES USED TO QUALIFY EFFECTIVENESS			
Device effectiveness	high	medium	low

TABLE 3 - SUMMARY OF THE INFORMATION PROVIDED IN CHAPTER 2					
Device	**Situation**				
	Normal conditions	**Traffic congestion**	**Breakdown or other minor incident**	**Serious incidents or accidents**	**Fire with evacuation order**
Traffic lights	NO (green lights only, when planned)	YES	YES	YES	YES
Lane control signals	YES (adapted to normal needs)	YES (if necessary)	YES (if necessary)	YES (if necessary)	NO
Tunnel lighting	NO (adapted to normal needs)	NO (adapted to normal needs)	YES	YES	YES
Variable message signs	NO (“*white messages*” only)	YES	YES	YES	YES
FM or DAB radio messages	NO	YES	YES	YES	YES
Mobile phones	NO	NO	YES	YES	YES
Tunnel closure systems	NO	YES (depending on the context and normally without barriers)	YES (depending on developments)	YES	YES
Public address systems (loudspeakers)	NO	NO	Occasionally	YES	YES
Evacuation route lighting	NO	NO	NO	NO (evacuation only)	YES
Emergency phones	NO	NO	YES	YES	YES
Flashing exit route indicators	NO	NO	NO	NO	YES
Flashing exit location indicators	NO	NO	NO	NO (evacuation only)	YES
Sirens	NO	NO	NO	NO (evacuation only)	YES

TABLE 3 - SUMMARY OF THE INFORMATION PROVIDED IN CHAPTER 2					
Device	**Situation**				
	Normal conditions	**Traffic congestion**	**Breakdown or other minor incident**	**Serious incidents or accidents**	**Fire with evacuation order**
Sound beacon above emergency exits	NO	NO	NO	NO (evacuation only)	YES
Videophones	NO	NO	NO	YES	YES
Public address systems in emergency galleries or refuges	NO	NO	NO	NO (evacuation only)	YES (during evacuation)
Direction signs in cross connections	NO	NO	NO	NO (evacuation only)	YES

3. IMPLEMENTATION OF REAL-TIME COMMUNICATION SYSTEMS

This chapter introduces the means and prerequisites for the implementation of real-time communication with tunnel users. The aim is to give a better understanding of how the system could interact with the users as described in more detail in the proposed model outlined in *illustration 19.*

Chapters 4 to 6 aim to explain how the activation of these resources must be adapted to the circumstances. In order to ensure consistency with previous PIARC reports (particularly [1] and [2]) these chapters detail the appropriate communication systems for typical situations that users might encounter in road tunnels. These situations are detailed in *chapters: 4 – Congestion; 5 - Minor or serious incidents; 6 - Fire*.

Other specific situations can also be taken into account (e.g. presence of pedestrians, suspicious parcel, debris, etc.). Using the examples for the typical situations, listed above, the implementation of real-time communication systems must be adapted to these different situations.

As indicated in the introduction chapter, *chapters 4 to 6* do not include an exhaustive list of all of the systems covered extensively in the PIARC report [1]. They explain why and how strategies for real-time communication with users must be adapted to the circumstances for each situation. These strategies must be defined in a global systematic approach (taking into account the interaction between user behaviour, vehicles, operations and tunnel equipment). These chapters take current knowledge of user behaviour into consideration. They also list all real-time communication systems likely to be activated in each of these situations.

If the tunnel infrastructure does not have all these resources at its disposal, the systems must be adapted accordingly, taking into account the intended aims in terms of user safety.

Illustration 19 summarises two key design aspects: the use of the tunnel real-time communication systems and the egress time model (*chapter 1.3* and *illustration 3*). It demonstrates when the real-time communication systems are active or are to be activated, and how they are to form an integral part of the tunnel evacuation strategy. This illustration also takes into account the human response to these systems by the tunnel users, as well as any of the other potential environmental aspects they perceive. It should be noted, that in the diagram the individual real-time communication systems are not directly linked to the egress model event periods but are to be seen as a generic entity.

During normal operation, the tunnel typically provides lighting, traffic lights to control the flow of the traffic as well as lane control systems. These will be enhanced by variable message signs, radio messages, mobile phone message or even future in-vehicle systems that provide the drivers with further information as to the traffic and driving conditions within the tunnel. In the event of an incident within the tunnel, the use of these systems will be enhanced by additional systems provided to manage and fully co-ordinate the incident, in line with the emergency procedures and the evacuation strategy.

For example, the lighting systems will be operational as part of providing normal driving conditions prior to an incident. When the nature of the incident has been recognised in the control centre, and alarm systems activated, the emergency lighting systems are to be activated. These systems could include the tunnel emergency lighting system, the evacuation route lighting system and the flashing exit route indicators as well as an emergency siren. These would then be able to provide the tunnel users with additional cues to assist them in recognising the need for evacuating as well as the escape routes that are to be used.

In terms of evacuation; once an alarm has been initiated, tunnel users require a certain period to recognise an alarm and then respond to it. These two periods are generally known as the pre-movement time. Once users are actively moving to escape from the tunnel this is known as their travel time. The combined periods of the pre-movement and the travel times make up their evacuation time. From a fire safety point of view this time is also referred to as the required safe egress time (RSET). The RSET time has to be less than the available safe egress time (ASET).

There are no specific timings for each of these periods as these are very dependent on human behaviour which can be influenced by active systems such as the real-time communication systems.

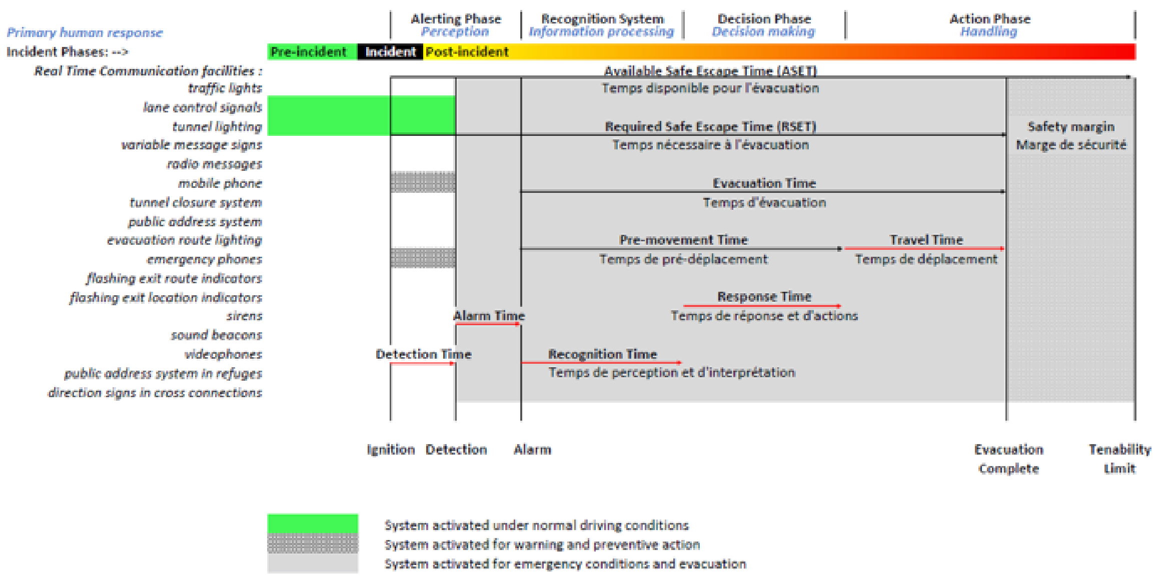

Illustration 19 - Facility activation in case of fire based on the egress time model

4. ILLUSTRATION OF USE IN CASE OF CONGESTION

4.1. DESCRIPTION OF THE SITUATION, FEARED RISKS

Congestion in road tunnels is a particularly feared situation, mainly due to the risk of a more serious situation developing. These situations occur when traffic is totally stopped in the structure, but may also include situations with very slow moving traffic, liable to endanger user safety. The notion of congestion is in this case often difficult to establish. Congestion may be a frequent phenomenon at rush hour in urban tunnels. It can also occur in less exposed tunnels which experience episodic traffic (often seasonal). The main feared risks in the case of congestion are: pollution, subsequent incidents or even the initial event turning into a breakdown or fire. The concentration of vehicles in the structure with, as a corollary, the problems this causes for the access of emergency and rescue services in the case of a serious event also constitutes a major source of concern.

Feedback has shown that most subsequent incidents occur at the end of the queue. In this respect, a lesson that has been learnt is that it is strongly recommended to make the relevant announcement before the end of the queue. The following resources are likely to be used in this context: **variable message signs** and **radio messages used in combination with appropriate queue or congestion detectors for automatically triggering the real-time communication systems.**

4.2. RESOURCES USED AND OBJECTIVES OF THE MEANS OF COMMUNICATION

The communication devices likely to be implemented in case of congestion are similar to those used under normal conditions. The tunnel equipment concerned consists of: traffic lights (flashing red or amber), lane use signals, variable message signs, and radio messages. The activation of these devices in the event of congestion is aimed at informing users of the situation and preparing them to react appropriately if need be.

Other resources may also be used in the case of congestion, such as tunnel closure systems. These systems must be activated in accordance with the provisions stated in the tunnel emergency response plan and when the circumstances demand it (to be assessed on a case by case basis and according to the risks listed above). Whether these systems are installed at the entrance or in the interior zone of the tunnel, the purpose of their activation is to rapidly reduce the number of people liable to be exposed to an existing or potential risk. Other additional objectives when closing a tunnel in case of congestion are to reduce the vehicle stationary time inside, to avoid claustrophobia or ventilation needs and to limit the number of vehicles (people) inside that may need to be evacuated in case of crisis.

5. ILLUSTRATION OF USE IN CASE OF MINOR OR SERIOUS INCIDENTS EXCLUDING FIRE

5.1. DESCRIPTION OF THE SITUATION, FEARED RISKS

This chapter deals with minor and serious incidents excluding fire. Serious incidents in this sense involve one or several vehicles or correspond to situations requiring emergency care and for which there may be an immediate danger for life (e.g. accident). Minor incidents represent situations without injuries such as breakdown in road tunnels (flat tyre, mechanical breakdown, etc.).

Serious and minor incidents may occur anywhere in the tunnel (traffic lane, hard shoulder, lay-by, etc.). They can obstruct one or several traffic lanes. However, depending on the geometry of the tunnel, some facilities provided for stopping can also be used in case of breakdown. This is the case when the user can reach a lay-by, stop on the hard shoulder or as close to the wall as possible. Many of these breakdown situations do not lead to the obstruction or closure of traffic lane(s). Consequently, the activation of existing real-time communication devices must be adapted to suit the location and nature of the breakdown.

Both types of incidents are dealt with in this sub-chapter because both of them generally require the use of similar communication systems. These resources must be activated in accordance with the provisions of the appropriate emergency response plan and when the circumstances demand it. A breakdown in a traffic lane, a lay-by or on the hard shoulder may require differing traffic management strategies. A large-scale incident involving several vehicles will also require a different emergency response.

The feared risks associated with an incident situation are the same as those identified with regard to the congestion situation. They can be associated with two other risks: subsequent incidents and delayed access for emergency services (because of congestion). In this particular situation it is important to mention that inappropriate behaviour of users may delay the arrival of emergency and rescue teams and endanger injured users who need emergency care.

Such an incident may develop into a fire: this situation will require evacuation and is illustrated in *chapter 6* of this report.

5.2. RESOURCES USED AND OBJECTIVES OF THE MEANS OF COMMUNICATION

Two categories of users must be distinguished in case of an incident situation: the driver(s) and the passengers of the vehicle(s) directly involved, and the other users who are driving at the location or approaching the location of the incident.

If the incident is an accident and all the people involved are injured, the alert would generally be given by another user. This user can therefore be considered as a directly involved user.

With regard to the driver and the passengers of the vehicle(s) involved, the first means of communication likely to be activated are the emergency phones. The objective of using the emergency phones is to report an incident and to help the control centre operator to locate the incident as quickly as possible. In tunnels which are not equipped with automatic incident detection this can be very helpful to the control centre operator to locate the event. This device also enables the control centre operator to communicate relevant instructions to users, encourage them to pay attention to the instructions of operational staff and adopt appropriate behaviour.

As mentioned in the report (PIARC, [2]) a call from a mobile phone is an alternative. In the tunnel such a call should only be made in an emergency, and when there is no safe alternative. However, people generally do not understand this and will likely use a mobile phone. A call from an emergency telephone indicates to the control centre operator exactly where the call is being made from. Calls from mobile phones cannot be located precisely and might delay the alarm to the control centre operator and the intervention of emergency services because the user may not actually know exactly where he or she is, or even the name of the tunnel. Users should be encouraged to use emergency phones when available in the tunnel rather than their mobile phones. However, some tunnels advise the use of mobile phones in the event of an emergency (*chapter 2.6* for details).

In addition, feedback has shown that users increasingly use their mobile telephones to report incidents in tunnels. In order to provide the location of the incident to the control centre operator, it may be worthwhile considering the option of installing positioning systems in the structure. These systems can also facilitate communication between the tunnel operating body and the emergency services in case of crisis.

The option of using mobile phones as a means of raising an alarm could be considered as a worthwhile operational solution for disabled users or for those accompanied by passengers who cannot be left unsupervised in the vehicle.

With regard to other users, the types of communication devices likely to be used in the event of an incident are similar to those activated in cases of congestion. **Traffic lights, lane control signals, variable message signs** and **radio messages** are the main types of equipment required to prevent a subsequent accident (fire, etc.). These resources can also be very helpful in order to optimise traffic flow and facilitate emergency intervention. Increasing the level of the **tunnel lighting** can also improve visibility in the area of the incident. In some countries public address systems are used to improve information to users involved in the incident. Depending on the severity of the incident, **tunnel closure systems** can be activated in order to reduce the number of users likely to enter the tunnel and approach the incident site.

The additional challenge relating to serious incidents is to optimise the traffic flow at the location of the incident as well as to protect the maintenance and intervention staff. In case of a serious incident, optimising the traffic flow should be a priority to facilitate access for the emergency services in the vicinity of the incident. Inappropriate user behaviour may delay the arrival of emergency and rescue teams and endanger injured users who need emergency care.

6. ILLUSTRATION OF USE IN CASE OF FIRE

6.1. DESCRIPTION OF THE SITUATION, FEARED RISKS

The main risks in the event of a fire breaking out in a road tunnel are obviously linked to the confined nature of the structure:

- firstly the release of smoke (this steadily becomes very opaque and disabling, unsettling users and making it difficult for them to orientate themselves and proceed to the emergency exits);
- then, users who have not evacuated the tunnel will be affected and may even be asphyxiated by the increasingly toxic smoke;
- finally, the heat of the fire causes high temperatures ("*furnace effect*") which can become intolerable for the human body.

The risks relating to a possible subsequent incident and the difficulties associated with the progress of the emergency services can be added to these direct consequences.

With regards to the evacuation of people, regulations generally exist that detail the facilities that need to be provided to users to ensure their safety and protection during an evacuation, with particular attention paid to actions before the arrival of the rescue services. During this period, which is critical for survival, users have to rely on their own initiative. The most significant developments on this point have led to an increase in the number of emergency exits, reinforcement of equipment for communicating with users and special efforts in terms of signalling. In the event of critical situations, users are expected to leave their vehicles and proceed on foot to the emergency exits. The analysis of various events, in new or refurbished tunnels, has shown that users frequently do not behave in a prescribed manner. They prefer to wait in their vehicles or evacuate the structure by making a U-turn or driving in reverse gear – rather than leave the vehicle and go to an emergency exit on foot.

In the event of a fire the main objectives of the means of real-time communication with users are therefore to:

- enable the users directly involved in the fire to send a message to alert the control centre operator;
- help all users to rapidly become aware of the situation;
- encourage them to leave their vehicles and proceed to the emergency exits;
- encourage them to use the emergency exits and go outside if possible or remain there until help arrives;
- warn of the imminent operation of other systems such as fixed fire fighting systems (where installed).

For more details on these matters, please see the table Main factors that accelerate occurrence of egress behaviour outlined in *chapter 3, page 46* Fires of the report (PIARC, [1]).

6.2. RESOURCES USED AND OBJECTIVES OF THE MEANS OF COMMUNICATION

The use of real-time communication systems in the event of a fire can be allocated to the main phases identified in the evacuation model discussed in *chapter 1* of this report. These phases can be summarized as follows:

- event detection phase and tunnel operating body alarm phase,
- general user alarm phase,
- tunnel evacuation phase,
- evacuation phase in emergency exits and while waiting for rescue services,
- phase of return to vehicle and end of incident.

The corresponding activation arrangements are described below for each of these phases.

Event detection phase and tunnel operating body alarm phase

In the event of a fire, it is extremely important to reduce detection time and the time taken to raise the alarm. The control centre operator may be alerted by automatic detection systems (automatic incident detection, video-surveillance, opacimeter, etc.). The alarm may also be given directly by users via real-time communication systems, mobile phones or emergency phones (*chapter 5.2*). During this phase, the control centre operator will receive the alarm, and then confirm the incident and decide on the appropriate response scenario.

During the phase preceding this trigger, no means of direct communication with users is yet operational for providing assistance. Only training and information can lead them to suspect a possible crisis situation in view of the events taking place in the structure.

General user alarm phase

The importance of this phase is to make the user understand that the situation is no longer normal, that it has changed to a crisis situation and that it is no longer possible to continue with the journey. Any and all methods which assist users in reaching the decision to evacuate should be considered.

If compatible with the level of tunnel operation, it is preferable to attempt to inform users of the situation inside the tunnel and the dangers faced and, if possible, to issue a clear evacuation instruction. During this phase, the sequencing of different sound and visual messages can clear all ambiguity in the minds of users regarding what is happening and make them aware of the change to a crisis situation. The following systems can be used in this context:

- broadcasting of appropriate **radio messages**, explaining the situation and the dangers involved and giving instructions to be followed;
- activation of a **tunnel closure system** with a stop light and associated Variable Message Sign. The objective of these tunnel closure systems is to reduce the number of users likely to enter the tunnel and to approach the fire;
- **sirens:** the purpose of the siren is not to make users leave their vehicles immediately, but rather, to make users aware that the situation has changed to a crisis situation and that they are in danger. An alternative facility (not compatible with sirens) is a "*public address system*". The effects can be similar, but this system also provides information to users in addition to an alert;
- **sound beacons:** during this phase, the purpose of sound beacons installed above the emergency exits is to trigger a general alarm for users if there is no siren system and to confirm the alarm after the siren has sounded by providing information and clear instructions to users (the message "*Attention - Danger – Exit here*" provides users with the information they need after hearing the siren). Sound beacons are also intended to help users to locate the exit in a smoke-filled environment and encourage them to reach the exit;
- activation of **flashing exit location indicators** placed on either side of the exit: during the alarm phase, the purpose of flashing lights is to provide visual information on the change of situation and reinforce audio messages. They also allow users to identify the position of exits and guide them in the right direction;
- activation of **flashing exit route indicators** (e.g. chevrons) placed on either side of the exit: these indicators are activated for a similar purpose to the flashing exit location indicators (provide visual information on the change of situation, reinforce sound messages, allow users to identify the position of exits, guide them in the right direction). These indicators are also intended to encourage users to pass through the exit.

These systems can be considered only in tunnels with human supervision, where the tunnel operating body can trigger the process. They are particularly relevant for urban tunnels and/or for tunnels with recurring congestion, where users are used to slowing down and stopping in the tunnel and will find it hard to distinguish between "*normal*" congestion situations and stoppage due to serious incidents.

Tunnel evacuation phase

During this phase, the aim is to guide the user in finding and moving towards the nearest exit. This objective is relevant even when environmental conditions in the structure are highly degraded and, in particular, when the regulatory signs placed at the location of exit doors are hidden by smoke. In addition to regulatory signalling, in tunnels where the control centre operator can activate the process, it is recommended to allow the additional systems, previously activated during the generalized alarm phase, to continue to function. They complete the user guidance system in a smoke-filled environment and help users to locate the exits.

It is reminded that the relevant devices are as follows:

- activation of evacuation route lighting, flashing exit location indicators;
- announcement of messages via the sound beacons installed above the exits.

These actions also help to reinforce and confirm the alarm.

Evacuation phase in emergency exits and while waiting for rescue services

In addition to regulatory measures concerning the installation of sound systems in shelters and waiting areas, such systems may also be installed at exits or assembly points for establishing transmission and reception contact between the tunnel operating body and those being evacuated. The relevant devices are: mobile telephone network service, videophones or emergency phones, public address systems.

However, although this solution appears worthwhile in terms of continuous and instantaneous communications, it should not be considered without particular precaution. In fact, it calls for a particular organisation and significant resources to ensure effectiveness. Even if the announcement of pre-recorded messages is relevant at the opening of the emergency door and arrival in the grouping area, this system rapidly reaches its limits, because, in order to be credible, the message communicated has to be adapted to the situation. If this solution is adopted, operating staff should be trained in the announcement of real-time messages, to ensure that they are able to provide information based on the actual situation, while managing the stress and impatience of waiting users.

Phase of return to vehicle and end of incident

Users must be informed when the incident, for which evacuation was necessary, has come to an end. One method of informing users is for intervention services to accompany the users back to their vehicles. If this approach is not possible, then the control centre operator should provide audio instructions, using the Public Address system, on how to return to the tunnel and the vehicle. At the end of the incident, gathering information on the incident from a user perspective and how the situation was managed should be shared with all the emergency services so that any improvements to dealing with future situations can be implemented.

Particular attention must be paid to this stage during the revision of the emergency response plans, notably for facilitating the handling of waiting users.

7. CONCLUSIONS

The knowledge acquired through research is based on how different crisis situations develop and improves the understanding and explanations of the differences detected between the expected and the actual behaviour of users in case of fires in road tunnels. While, to date, regulations and policies have focused on equipment, organization and operation-related aspects in order to improve the safety of users, new approaches are emerging aiming to better adapt structures to user behaviour.

In this vein, and in application of the results of various research projects, the specific provisions presented in this document can offer solutions able to initiate appropriate behaviour by users. Major stakes are involved here for all tunnels, but particularly for urban tunnels with dense traffic or for tunnels where recurrent congestion makes it very difficult for users to distinguish real crisis situations.

If these provisions are implemented, it is essential to back application up with the means of communication necessary for learning purposes, via initial or refresher training, or, more generally, by providing appropriate information. In addition, it is preferable to continue the "*in situ*" evaluation of these systems during their deployment, by allocating volunteer users to ensure that the new signals are interpreted correctly.

Lastly, it is also necessary to draw the attention of tunnel managers to the importance of providing sufficient resources for the real-time implementation of the proposed system as well as their maintenance by the tunnel operating body. If required, rather than trying, at all costs, to multiply such systems, making their management more complex, it may be more relevant to only adopt some of the systems described here, taking into consideration the context of the structure as well as the availability of resources.

In order to optimize these choices it can be helpful to take into account the priorities as proposed in *chapter 2*.

Pending this additional information, the working group suggests that those wishing to implement this type of device should pay attention to the following recommendations:

- depending on the internal context of each country, it is important, first of all, to comply with the installation priorities defined in existing regulations. For example, in France, regulations provide that "*If radio broadcast stations are relayed, and if there is a control unit, it must be possible to interrupt these relays in order to broadcast safety messages to users*" and the EU Directive also imposes this measure;
- beyond the specific regulations applicable in each country, experience has shown that the **tunnel closure system** is an extremely valuable safety equipment in case of a serious incident;
- at the location of an emergency exit, the following systems seem to be worthwhile in terms of results: **flashing exit location indicators** and **sound beacons**;
- during the evacuation phase, the sequencing of different sound and visual messages can clear all ambiguity in the minds of users regarding what is happening and ensure their awareness of the changeover to a crisis situation. Trials are underway in several tunnels for the following working approaches:
  - installation of sirens for raising the alarm,
  - installation of sound beacons warning of danger and giving the instruction to leave the tunnel via the emergency exits,

– activation of flashing exit position indicators and flashing exit route indicators,
– these facilities are particularly relevant for urban tunnels or for tunnels with recurring congestion, where users are used to slowing down and stopping in the tunnel and will find it hard to distinguish between "*normal*" congestion situations and stoppage due to serious incidents;

- when these systems are implemented, it is essential to provide support via training and information to familiarise users with these systems (PIARC, [2]);
- it is also necessary to draw the attention of tunnel managers to the importance of providing sufficient resources for the real-time application of the proposed provisions as well as their maintenance by the tunnel operating body.

In tunnels with permanent surveillance, where the tunnel operating body is able to trigger the process, the following are also recommended:

- broadcast appropriate radio messages explaining the situation and the dangers involved and giving instructions;
- associate a tunnel closure system (closing access to the tunnel) with a variable message sign.

When designing and implementing these facilities, it is essential to pay attention to consistency between: the facilities themselves, the activation strategy for these facilities, pre-recorded (or live) messages and the context of the event.
In addition to these tunnel facilities, the existing "*in-vehicle systems*" listed in *chapter 2.18* can provide additional information to help users adopt the appropriate reactions. Systems still in the development phase can be considered as "*high expectation*" systems in the context of this report.

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GLOSSARY

Term	Definition
Static facility	Item of equipment of a fixed or stationary nature.
Dynamic facility	Item of equipment capable of adapting to changing tunnel conditions.
Tunnel closure system	Set of equipment (usually made up of at least lights and signs, ideally completed with barriers) used to prevent users from entering the tunnel or approaching the scene of an accident.
Public address system	System based on a set of loudspeakers used to broadcast pre-recorded or live messages inside an infrastructure.
Evacuation route lighting	Lighting system provided to guide tunnel users that are evacuating the tunnel on foot towards emergency exits, in the event of an emergency.
Flashing exit route indicator	Arrows used to guide users to emergency exits in case of tunnel evacuation. This equipment is located along a distance of several meters either side of an emergency exit, thereby indicating the exit route to users approaching from either direction.
Flashing exit location indicators	Flashing lights used in case of tunnel evacuation, indicating the location of emergency exits to users.
Siren	Sound system used to signal an alarm, characterized by its frequency, its duty cycle and volume intensity.
Sound beacon systems	Loudspeaker located at emergency exits and used in case of tunnel evacuation. The beacon may emit a specific sound combined with messages, to help users locate the exit and provide them with appropriate evacuation instructions.
Video phone	Telephone with an added video functionality allowing its users to see each other while talking.
Marker lights	Permanent lighting (fitted on the sidewalls at a height of no more than 1,5 meters or on the pathway). The objective of this lighting is to guide users to emergency exits.
Cooperative systems	With ITS (Intelligent Transportation Systems) technology, Cooperative Systems are the group of systems that can obtain, share and distribute information about infrastructure status and environmental conditions. This technology can be split into I2V - Infrastructure to vehicle, and V2V - Vehicle to Vehicle technology. The goal of cooperative systems is to use and plan for communication and sensor infrastructures to increase road safety.
Lane departure warning system	In road transport terminology, a mechanism designed to warn a driver when the vehicle begins to move out of its lane (unless a turn signal is on in that direction).
Radar distance control	System provided on some modern cars in addition to the automatic cruise control. The device uses a radar or laser to measure the distance and speed of approaching vehicles ahead of the user and adjusts speed automatically to avoid a collision, before returning to the initial velocity when the obstacle is no longer present.
Tunnel operating body	The organisation responsible for the operation of the tunnel. May be the Tunnel Owner or a subcontractor of the Tunnel Owner.
Tunnel control centre operator	Employee of the Tunnel Operating body in charge of all or part of the operation of the tunnel at a given moment (may be several persons with separate responsibilities, for example traffic operation and technical operation). The control centre operator can ensure either: only traffic operation (in this case he is the traffic operator and there is a separate technical operator) or both traffic and technical operation (in this case he is the unique control centre operator).
WhatsApp	A cross-platform mobile messaging application which allows messages to be exchanged using available access to Internet Networks.

ACRONYMS

ENGLISH		FRENCH	
Term	**Definition**	**Terme**	**Définition**
CCTV	Closed-circuit television		
DAB	Digital Audio Broadcasting	DA	Diffusion Audionumérique
FM	Frequency modulation -	FM	Fréquence Modulée
GPS	Global Positioning System	GPS	Système global de localisation
I2V	Infrastructure to vehicle		
IRC	Canadian Institute for Research in Construction	IRC	Institut Canadien pour la Recherche en Construction
LED	Light-Emitting Diode	DEL	Diode Electro Luminescente
RDS TMC	Radio Data System Traffic Message Channel	RDS TMC	

V2V	Vehicle to vehicle		
VMS	Variable Message Sign	PMV	Panneau à Messages Variables

APPENDIX

"TIME POSITION DIAGRAM"

Illustration 20, next page is intended to graphically summarize some of the concepts developed in this report.
The central idea is to represent the self-evacuation of three groups of road users, like in a risk analysis, and connect it to both the activation of the real-time communication facilities (explained in *illustration 19*) and the egress time model (explained in *illustration 3*). In addition, the facilities are located on the tunnel synoptic.

Illustration 20 includes 4 complementary parts described hereafter.

- 1st, a synoptic plan view of a one-way tunnel with 2 lanes is illustrated in the central upper section. The different real-time communication systems explained in this report (circles numbered from 1 to 17 accordingly with the chapters of this report) are shown. Those which are installed all along the tunnel (3, 5, 6, 8, 9, 13) are linked with a dotted line.

The real-time communication systems and their associated numbers are reiterated in the upper left section.

- 2nd, the left section shows the activation of each of the 17 real-time communication systems depending on time. The vertical axis, representing time, is graduated in minutes. It is shared with the space/time diagram shown in the central section. The origin of time corresponds to the "*incident*". The public address system, sirens and sound beacons system must be activated alternately to remain coherent and efficient. The duty cycle represented is purely informative (for illustrative purposes).
- 3rd, the central section shows the tunnel length horizontally (aligned with the tunnel synoptic) and time vertically (aligned with the system activation chart on the left and with the egress time model phases on the right). The green lines (vs. the blue lines) correspond to the movement of vehicles (vs. the movement of walking road users). In this space/time diagram, a vertical line means that the element is immobile (not moving along the tunnel) whereas a slanted line indicates a longitudinal movement (the more horizontal the line, the faster the movement).
- 4th, the right columns (aligned with both the left and the central parts) reiterate the succession of the egress time model phases and provide partial explanations of the space/time diagram. The behaviour of three groups of road users is briefly described, highlighting the main differences and stakes according to the distance from the location of the fire.

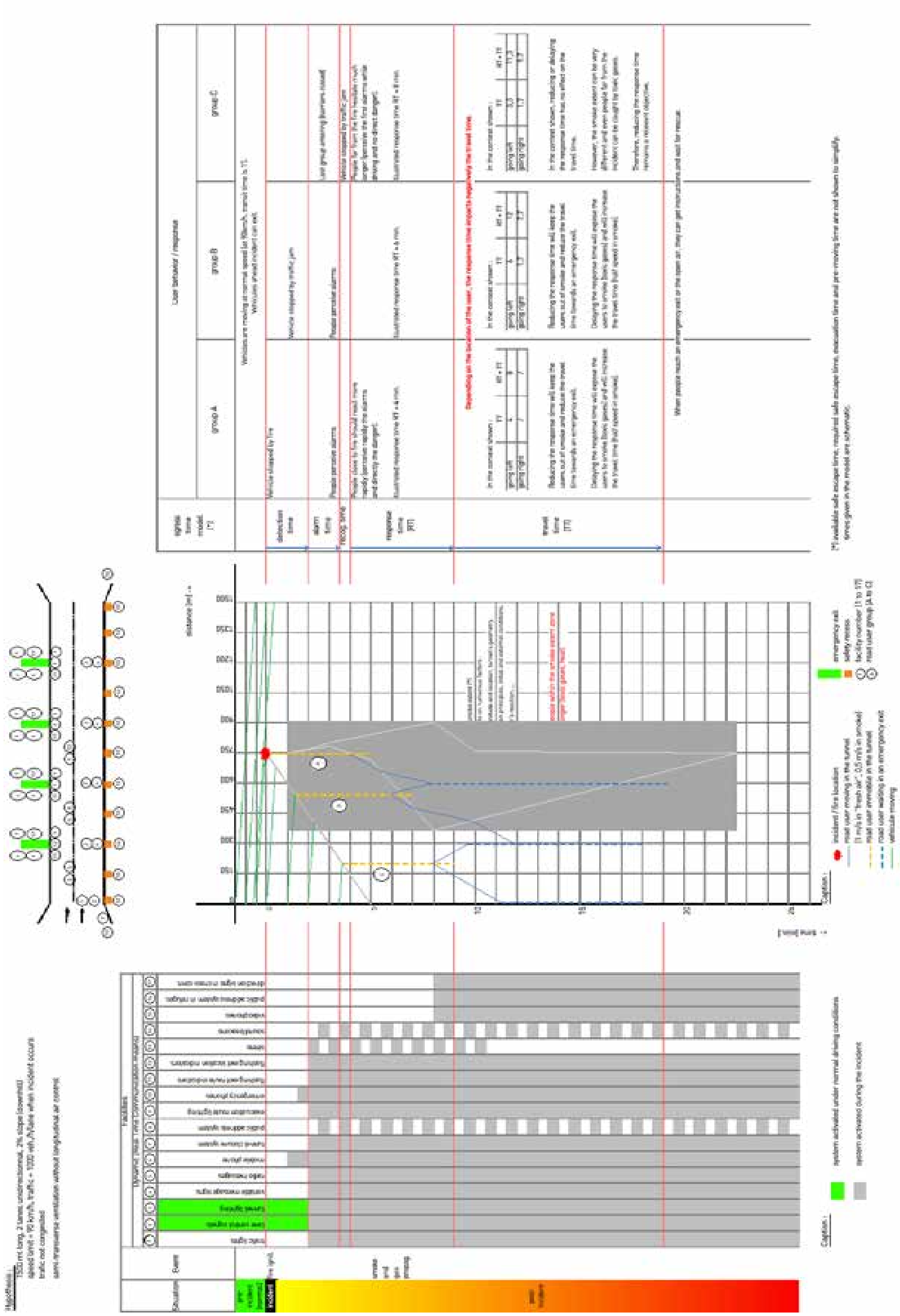

Illustration 20 - Example of a time position diagram for safety margins

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