Traffic Information Signs, Colour Scheme of Emergency Exit Portals and Acoustic Systems for Road Tunnel Emergency Evacuations

Ronchi, Enrico; Nilsson, Daniel

2013

LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

Traffic Information Signs, Colour Scheme of Emergency Exit Portals and Acoustic Systems for Road Tunnel Emergency Evacuations

Enrico Ronchi
Daniel Nilsson

Department of Fire Safety Engineering
Lund University, Sweden

Brandteknik och riskhantering
Lunds tekniska högskola
Lunds universitet

Report 3173
Lund 2013

Traffic Information Signs, Colour Scheme of Emergency Exit Portals and Acoustic Systems for Road Tunnel Emergency Evacuations

Enrico Ronchi
Daniel Nilsson

Lund 2013

Traffic Information Signs, Colour Scheme of Emergency Exit Portals and Acoustic Systems for Road Tunnel Emergency Evacuations

Enrico Ronchi and Daniel Nilsson

Report 3173

Number of pages: 50

Illustrations: Enrico Ronchi and Daniel Nilsson.

Keywords: Emergency evacuation, tunnel evacuation, Theory of Affordances, way-finding, notification, emergency exit, and system design.

Abstract. This work presents a literature review and a questionnaire study with 62 participants aimed at providing recommendations on the design of a set of evacuation systems for road tunnels: 1) Traffic Information Sign (TIS) - message and size of the sign (large or small), colour scheme, and use of pictograms and/or flashing lights, 2) Emergency exit portal layout - colour scheme, 3) Acoustic systems - voice message and/or warning signals. The TIS is recommended to include the use of two panels which present text (in amber) and flashing lights in one panel and the emergency exit pictorial symbol in green in the other panel. An increased size of the panels has a positive effect on capturing participants' attention. The recommended colour scheme for the emergency exit portal is safety green for the portal and a "green darker than the safety green" for the door. Vocal messages are not recommended since they may be quite difficult to perceive in tunnels. The use of a warning signal (F_SAW signal) based on British Standards is recommended.

Brandteknik och riskhantering
Lunds tekniska högskola
Lunds universitet
Box 118
221 00 Lund

brand@brand.lth.se
http://www.brand.lth.se

Telefon: 046 222 73 60
Telefax: 046 222 46 12

Department of Fire Safety Engineering and Systems Safety
Lund University
P.O. Box 118
SE-221 00 Lund
Sweden

brand@brand.lth.se
http://www.brand.lth.se

Telephone: +46 46 222 73 60
Fax: +46 46 222 46 12

Acknowledgement

This work is part of the “Stockholm Bypass, tunnel safety studies”, co-funded by the EU Trans-European transport network (TEN-T). The work presented in this report is a sub-part of “Stockholm Bypass, tunnel safety studies” and it is called “Evacuation route design” (Utformning av utrymningsväg). The results presented in this report will be used to assist the design of the evacuation systems in the Stockholm Bypass project by Trafikverket.

This work would not have been possible without the help of Henric Modig (Trafikverket and Faveo Projektledning) and Anders Lindgren Walter (MTO Säkerhet). The authors also wish to acknowledge Sara Petterson (MTO Säkerhet), Andrew Pryke (Faveo Projektledning) and Jörgen Norén (Lund University) for their support.

Co-financed by the European Union

Trans-European Transport Network (TEN-T)

Summary

This document is intended to assist road tunnel safety designers and operators in the assessment of the appropriate emergency systems in the case of road tunnel evacuation. In particular, the present work discusses the design of Traffic Information Signs (TIS), the colour scheme of emergency exit portals as well as acoustic warning systems (e.g., warning signals). This report is part of the research project "Evacuation route design" (Utformning av utrymningsväg) funded by the Swedish Transport Administration (Trafikverket). Different systems for road tunnel evacuation emergencies are tested and evaluated within this research project. The results presented in this report will be used to assist the design of the emergency systems in the Stockholm Bypass project. A literature review is performed to provide input to the selection of possible designs for the above mentioned systems. The designs are evaluated using the Theory of Affordances.

A set of TISs are qualitatively evaluated. TISs systems under consideration consisted of two rectangular TIS panels conveying information to motorists and three intermediate smaller squared signs. The Theory of Affordances is used to evaluate a preliminary set of eleven TIS systems. Based on the evaluation, six TIS designs were selected and further evaluated using an affordance-based questionnaire study with a sample of 62 participants. Results of the analysis based on the theory of Affordances as well as the questionnaire study are used to provide recommendation on the design of the characteristics of the TIS systems. Optimal TIS systems include the use of two panels which present text in one rectangular panel and a pictorial symbol in the other rectangular panel. Amber is the colour recommended for the written text in the panels. Flashing lights result particularly effective on increasing the attractiveness of the TIS and the subsequent attention of the test participants. Two different sizes of the panels have been tested. An increased size of the panels available in the TIS has a positive effect on capturing participants' attention. For this reason, designers should take into account that an increased size of the panels can substantially affect the effectiveness of the TIS system and provide bigger sizes of TIS whether it is possible. Recommended TIS designs include a combination of pictorial symbol and text in two different panels. Further studies are needed to investigate the use of different languages (e.g., English and Swedish in this instance) in relation to different types of tunnel users. The use of the emergency exit pictorial symbol in green resulted as the most effective pictorial symbol if compared with warning and do not enter symbols.

The qualitative system evaluation using the Theory of Affordances permitted the identification of suitable solutions for the design of emergency exit portals and acoustic warning systems. The analysis revealed that emergency exit portals should be designed with a green colour scheme. Appropriate contrast should be given to the colour of the emergency exit door inside the portal. The use of a darker green is recommended for the emergency exit door.

Acoustic systems are evaluated using the Theory of Affordances. In the case of road tunnel, the use of vocal messages is not recommended due to possible issues associated with background noise. A warning signal based on British Standards (a saw-tooth signal) is recommended. The recommended signal has a pulse rate of at least 1Hz and a frequency range of 0.8-1 kHz.

Table of Contents

1. Introduction

The understanding of the environment as a whole is the main base for real-time decision making. This concept is associated with a holistic perception of the environment (Endsley, 1995). In this context, way-finding systems may be a valid support, since they enhance people ability to perceive the environment. Way-finding systems are here intended in a general sense as any system which would assist users in way-finding during an emergency evacuation.

The present document includes the analysis of a group of selected systems adopted for way-finding during emergency evacuation in road tunnels. This analysis is a necessary step for the identification of a set of way-finding systems which are evaluated and ranked using the Theory of Affordances. In order to perform the analysis, a dedicated questionnaire-based experiment has been carried out. In line with the application of this research in the real world (i.e. to assist the design of the emergency systems in the Stockholm Bypass project), the following evacuation emergency systems have been investigated:

1) Traffic Information Sign (TIS): message and size of the sign (large or small), colour scheme, and use of pictograms and/or flashing lights.
2) Emergency exit portal layout: colour scheme.
3) Acoustic systems: voice message and/or warning signals

The present study analyses scenarios in which motorists are expected to leave their vehicles and walk towards a safe place, i.e., way-finding systems are not intended to encourage users to evacuate the tunnel using their vehicles.

In order to assist road tunnel safety designers and operators in the assessment of the appropriate emergency systems in the case of road tunnel evacuation, the following objectives have been identified:

1. To examine the current methods adopted to design TIS in road tunnels, including the type, length and content of the messages, size of the signs, visual systems (e.g., pictograms, colours, etc.);
2. To examine emergency exit portal design (e.g. colour scheme, etc.);
3. To examine the effectiveness of different acoustic systems (e.g. vocal messages and/or warning signals) to enhance emergency evacuation response in road tunnels.

2. Theory of Affordances

A useful framework for the analysis of the design of evacuation systems, e.g., fire alarms, way-finding systems or simple emergency exits, is the Theory of Affordances, which was originally developed by Gibson (1977). According to Gibson's original theory, an object is perceived in relation to what it offers or affords the individual. An affordance is, hence, what the object offers the individual in relation to his or her goal.

The Theory of Affordances has been used in a variety of different research fields to analyse the design of everything from climbing routes (Boschker et al., 2002) to human-computer interaction design (Hartson, 2003). It has also been used to evaluate the design of emergency exits (Sixsmith et al., 1988) and to explain the effectiveness of way-finding systems for evacuation (Nilsson et al., 2009). In addition, the theory has been successfully employed in fire safety research to understand evacuation behaviour (Joo et al., 2013; Kim et al., 2011; Nilsson, 2009).

In order to enable the analysis of the affordances provided by an evacuation system, it is useful to divide affordances into different categories. One possible division has been proposed by Hartson (2003), who suggests that affordances be divided into the following four categories:

1) Sensory affordance: <u>sensing or seeing</u>
2) Cognitive affordance: <u>understanding</u>
3) Physical affordance: <u>physically doing or using</u>
4) Functional affordance: <u>fulfilment an individual's goal</u>

It has been argued that the Theory of Affordances can be a useful tool for identifying potential design faults of evacuation systems early in the design process (Nilsson, 2009). By systematically exploring the sensory, cognitive, physical and functional affordances provided by an evacuation system, it should be possible to identify conflicts and non-optimal design. Hence, the theory can be used to analyse an array of possible system designs in order to rule out the least appropriate system. However, this type of analysis requires ample understanding of the different types of affordances in relation to the examined system. The following sections therefore provide brief explanations of the four categories of affordances in relation to the types of systems that are studied in the present report, i.e., in relation to evacuation systems.

2.1. Sensory affordance

In order for an evacuation system to work as intended it must first be sensed, e.g., seen or heard, by the individual. This means that a design must provide sufficient sensory affordances to catch people's attention and be noticed. In addition, it must be possible to make out the details of the system, e.g., a written text message on an information sign should be legible and a voice alarm should be intelligible.

Previous research has shown that the contrast between the system and its surrounding influences sensory affordance. For example, if an emergency exit has the same colour or pattern as the walls it can easily be missed (Sixsmith et al., 1988). Similarly, a fire alarm with the same frequency as the background noise might not stick out, which suggests that a wide frequency range is appropriate to overcome a multitude of possible background noises (Palmgren and Åberg, 2010). Another way of increasing the attention capturing ability is to introduce an alternating pattern, e.g., flashing lights for visual systems (Nilsson, 2009) or pulsating sound for acoustic systems (Palmgren and Åberg, 2010). However, this still requires that the background does not alternate according to a similar pattern, and it is hence another way of providing contrast.

If an evacuation system is meant to convey complex information, it is particularly important that the details of the system can be easily discerned. For example, text provided by a visual evacuation system must be sufficiently large (Dudek, 1991). Similarly, it must be possible to make out the details of a pre-recorded evacuation message, which has been shown to be quite difficult in road tunnels due to the challenging acoustic environment (Nilsson et al., 2009).

2.2. Cognitive affordance

Cognitive affordances support the understanding of the observed evacuation system. This understanding is essential for the performance because inappropriate interpretations can lead to confusion and non-optimal behaviour. It is therefore essential to ensure that evacuation systems are properly understood, which can be achieved by consistent and well-considered designs.

In order to achieve appropriate cognitive affordances, i.e., to ensure that an evacuation system is interpreted as intended, it is useful to build on people's previous experiences and preferences. For example, the colour green can be used to signal *safety* or *go*, as these are the typical associations with green (Wickens, 2013). The colour red, on the other hand, can be used to keep people away because red is often associated with *danger* or *stop* (Wickens, 2013). Similarly, it might be possible to use pictograms with well-established meaning to convey a specific message.

The cognitive affordances provided by a specific design can also be influenced by the context, i.e., the nature of the situation. This is exemplified by the misinterpretation of the traffic information signs during the fire in the Södra Länken tunnel in Stockholm on June 16, 2008 (Åberg et al., 2008). The written message on the signs was to *"evacuate tunnel"*, which lead many motorist to drive out through the dense smoke instead of leaving their vehicle and evacuating on foot. This example shows that, from the perspective of the motorist sitting in their vehicle, the message was interpreted differently than the designers had intended. It is therefore important to consider the context of the situation and to provide clear information that is not easily misinterpreted.

2.3. Physical affordance

Physical affordance supports the user physically doing something, such as opening a door. This type of affordance is therefore mainly applicable for evacuation systems that are physically used during evacuation. Examples include opening devices for doors or buttons for initiating two-way communication. In order for these types of systems to work, it is imperative that people can easily use them and the design should ideally support this use by being simple to operate. For example, a door handle should be easy to operate and a door should not be difficult to push open, e.g., should not require a large opening force.

In the present study, only certain aspects of the design of TISs, emergency exit portals, and acoustic alarms for road tunnels are studied. Two of the systems, namely TISs and acoustic alarms, are not physically used during evacuation, but are instead intended to attract people's attention and convey important information. This means that physical affordances are not relevant for the two systems.

Emergency exit portals are physically used during evacuation in road tunnels, which means that physical affordances are relevant. For example, the design of the handle and the door leaf can potentially influence how difficult the door is to open. However, in the present study, only the colour scheme of exit portals is included, which means that mainly sensory, cognitive and functional affordances are relevant. Therefore, physical affordances are not discussed to a great extent in the present report.

2.4. Functional affordance

Functional affordance helps the user to achieve the desired goal and can be seen as the final outcome of the combination of sensory, cognitive and physical affordances. For road tunnels, the main goals should preferably be to reach a safe place, which requires people to overcome possible property attachment (Shields, 2005), i.e., not be reluctant to leave their vehicle, and normative social influence (Nilsson and Johansson, 2009). In order to achieve appropriate functional affordance, this goal needs to the reinforced by the evacuation system. For example, a TIS that is easy to notice (sensory), easy to read/see (sensory) and easy to understand (cognitive) will also provide appropriate functional affordance. For systems that are physically used, e.g., emergency exit doors/portals, it is also relevant to include physical affordance when estimating the functional affordance.

2.5. Conflicting affordances

If an evacuation system is designed inappropriately, it can provide affordances that are in conflict with each other. For example, a system consisting of a green emergency exit sign with flashing orange lights may provide cognitive affordances that are in conflict (Nilsson, 2009). The sign might signal that the exits should be used for emergency evacuation, but the orange light might be interpreted as a warning. Conflicts may also arise between different types of affordances, e.g., sensory and cognitive.

The concept of conflicting affordances is considered very useful for understanding why certain evacuation systems are inappropriate. By systematically examining the sensory, cognitive, physical and functional affordances provided by a specific design, it is often possible to identify potential conflicts at an early stage of the design process.

3. Traffic Information Signs

A Traffic Information Sign (TIS), also called Variable Message Sign, is a technology used in tunnels to provide users with real-time information. A TIS is a programmable electronic panel capable of displaying messages of different nature. Depending on the type of technology employed, the panel is capable of displaying messages made of text, pictograms or a combination of them. Recent visualization technologies employed in TIS, e.g., LCD screens, includes dynamic features such as the use of animation, flashing, scrolling, etc. This leads to a great flexibility in the content and type of information to be displayed to the users (Wang et al., 2006). On one hand, this allows a great range of possibilities to the designer of the TIS. On the other hand, it poses several questions on the information to be displayed in order to provide understandable and effective messages (Dudek, 1991; Dudek and Ullman, 2002).

In the case of a tunnel emergency, e.g., fire evacuation, TIS may be a useful tool to convey concise and precise information to motorists about an emergency as well as instruct them on the appropriate actions to perform to reach a safe place (Nilsson et al., 2009). In fact, TIS can be used as a procedural measure to influence route choice.

The observation of a sign in the road prompts an automatic, implicit response called *priming* (Koyuncu and Amado, 2008). In order to design effective systems, the stimuli prompted by a way-finding system should be tested in a data-driven or conceptually driven test. This should be made taking into account that perception and comprehension of a TIS can be considered as an identification task (Christ, 1975).

Several factors contribute to the effectiveness of a way-finding system made of a visual system. Different affordances should be considered during their analysis. In this section, the main issues associated with those factors are described (as they were listed by Wright (1968), including colour, lighting (e.g., the use of flashing effects), the size of the visual system, pictorial symbols and message design. The study is focused not only on the evaluation of sensory affordance (in terms of the visibility of the visual system), but also on cognitive, and functional affordances.

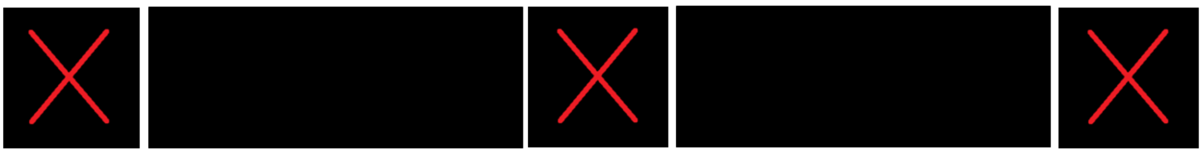
The case of tunnel emergency evacuation is a specific case since motorists may observe the TIS either during their journey inside the tunnel or while stopped in a queue. TIS should be designed in order to allow motorists' identification of letters/words/symbols on the panel while driving their vehicles. The maximum distance at which a driver can first correctly identify this information is called *legibility distance* (Dudek, 1991). In order to increase the probability of identification, signs should be placed in visible and expected locations (Borowsky et al., 2008). Design characteristics of TIS affect the legibility distance. The effectiveness of a TIS primarily depends on the design of its message and the display format (Wang et al., 2006). Driver's attitudes to respond to TISs may also be affected by demographics. A research study conducted in the United States (Wang et al., 2006) showed that women and young people are generally less inclined to comply with TIS advice. Key design parameters are the type of display technology (light-emitting, light-reflecting, etc.), height and width of the characters and symbols, the stroke width of the characters and the type of font displayed (Dudek and Ullman, 2001). Standard fonts are displayed in uppercase (Dudek, 1991).

A set of characteristics of the TISs are investigated in this report, namely colour design, written message design, flashing effects and pictorial symbols. A literature review has been performed to select a first set of possible designs for TISs. The evaluation of the designs has been performed with a two-step evaluation. In a first step, a preliminary analysis of the TIS designs has been carried out using the Theory of Affordances in order to exclude the TIS designs that were deemed to not perform well. In a second step, selected TIS designs were further evaluated through a questionnaire study based on the Theory of Affordances.

3.1. TIS design selection

In line with the objectives of the present study, a specific layout of information signs is investigated in this document. It consists of 2 rectangular TIS panels conveying information to motorists and three intermediate smaller squared signs (see schematic representation in Figure 1). This layout is selected in order to assist the design of a real-world tunnel (the Stockholm Bypass project). The TIS panels have a fixed dimension of 240x90 cm on the opposite side of the emergency exit and two possible dimensions on the side of the emergency exit, either 240x90 cm or a larger size of 240x170 cm. The intermediate panels have fixed dimensions corresponding to 90x90 cm. In the case of emergency, the smaller panels will be used to show red crosses which are used to encourage tunnel occupants to stop their vehicles.

Layout 1 – two TISs of the same dimension (both 240x90 cm).



Layout 2 – TIS on the side of the emergency exit is larger (240x170 cm and 240x90 cm).

Figure 1. Schematic representation of the layout of information signs under consideration. The layout may include two panels of the same size (top) or a larger panel on the side of the emergency exit (bottom).

3.1.1. Colour

Several studies have been carried out in order to investigate the effectiveness of different colours to provide information to the motorists (Christ, 1975; Lai, 2010, 2008; Pastoor, 1990). Colour codes are generally performing better for searching task than other type of codes such as the use of text, pictograms, etc. (Christ, 1975). Colour codes are also better for identification tasks than other types of code, but colour codes alone are not generally as good as letters or numerals for such type of tasks (Christ, 1975; Sanders, 1993).

Colour coding can be designed in line with international standards, e.g., ISO standards (International Standards Organization, 2011). Nevertheless, response times of users in recognizing and understanding the content of an object given the colour employed (cognitive affordance) may depend on the experience and meaning of the colour code in different countries (Chan and Ng, 2009; Lai, 2008). Cultural background is a critical factor in colour recognition and understanding, thus the design should take into account cross-cultural influences on the comprehension (Ou and Liu, 2012). Colour coding can be used to effectively present different classes of information in different colours (Wickens, 2004). In fact, colours have their own specific meaning in the field of transportation (Chan and Ng, 2009). For example, in Europe, red is generally used to represent a dangerous situation, amber is used for warning and green is used for safety (Lai, 2010). It should be noted that problems may occur when the meaning of the colour code is not known to the user or the colours are not properly correlated with the type of information displayed (Pastoor, 1990). A careful evaluation of colour coding is therefore recommended in the design of any type of way-finding system in a tunnel.

Experimental studies in the United States (Wang et al., 2006) and China (Lai, 2012, 2010, 2008) showed that people tend to respond faster and more correctly to amber and green colour rather than for red colour. Nevertheless, red colour is more effective than blue and amber/yellow in transmitting warnings (Chan and Ng, 2009). This is deemed to be associated with a high level of cognitive affordance that it generates.

In the case of the use of colour for written messages, the interaction between the style and the colour of the font has also been observed as a significant factor on people response performance (Lai, 2008). Amber and green colours have been observed to produce shorter response time than red colour for a range of font styles (Lai, 2008). Experimental studies showed that a compatible relationship between colours and messages may result in a lower response time for the case of a two-colour scheme rather than a single colour scheme (Lai, 2010; Wickens, 2004) with the use of black as background colour.

Selected colour scheme

In line with the literature review performed, a two-colour scheme is suggested for use for the background and the written messages. Examples of a three-colour scheme are provided as well. The suggested background colour of the TIS is black and the elements in the panel may be amber (i.e., yellow towards orange), red or white in relation to the type of information provided (e.g.

respectively warning message, danger, information, etc.) and the possible combined use of pictorial symbols.

3.1.2. Written message design

Different factors need to be taken into account during written message design. Message content refers to the information provided to the motorists. In the case of emergency information, this mainly consists of a description of the emergency type and the actions that motorists are required to performed.

In order to study message design, it is important to introduce the concept of *Unit of Information* (Dudek and Ullman, 2001). Unit of information refers to the brief answer to a question a motorist might ask. In this context, *message load* is used to describe the amount of information provided in the message (i.e., the number of units of information), while message information format refers to the order of the units of information.

Another important factor is the message length, intended as the number of words/characters in a message. General factors which affect message design include font size, number of message lines, wording and abbreviations (Wang et al., 2006).

The size of the font should be linearly related to the distance from which it is intended to be read (Borowsky et al., 2008; Shinar and Vogelzang, 2013). The character fonts and dimensions should undergo a legibility analysis prior to their implementation (Wang et al., 2006).

The visual search of the written message depends on the amount of information provided (Liu, 2005). During the design of a message, the amount of information contained in a single sign should be kept as small as possible in order to reduce people viewing time and the feeling of pressure (Liu, 2005). In addition, information should be appropriately separated.

People tend to have a lower response time for double line messages than the case of single and triple line messages (Lai, 2010). Messages with fewer lines generally lead to a faster response (Wang and Cao, 2003).

It is generally recommended to provide no more than three units of information in a single message frame (Dudek and Ullman, 2001). In the case a two-frame message is displayed, field studies demonstrated that the best response is obtained in the case of a 2 sec/frame or a 4 sec/frame display rate (Dudek, 1991). Common practice is to display each frame for two seconds in such a way that users can see a two-frame message displayed twice within the viewing distance (Wang et al., 2006). Multiple frames can also be used to display messages in multiple languages. Dudek and Ullman (2001) recommended that only a single unit of information should appear in a single line of TIS, while more than one unit of information may be displayed on more than one line.

TISs can contain three different types of information such as 1) the problem (i.e. the incident), 2) the location of the problem and 3) the recommended motorist action. Nevertheless, given sign space and legibility constraints it is not always possible to provide information on all elements (Dudek and Ullman, 2001). In all TIS designs, the action message is necessary since it provide the motorists the crucial information they need. In fact, an omission on the action to perform will create a great level of uncertainty to the motorists.

Based on a questionnaire study and laboratory experiments Wang and Cao (2003) suggested that TIS message should be with no or minimum flashing, very specific wording, without abbreviations and displayed in a solid amber or green-amber colour combination. Dudek and Ullman (2002) suggested that one-frame TIS messages should not be flashed, or a line on a one-frame message should be flashed and a line on a two-frame message should be displayed as an alternated message while keeping the other lines with the same message.

<u>Selected written message</u>

The selected written message in the panel is made of either one or two lines. Each line will contain only one unit of information. In the case of a 1-line message, the unit of information informs motorists on the main action to perform (to evacuate the tunnel or use the emergency exit). In the case of 2-line message, the two lines recommend motorists on the actions to perform in more detail (to turn off the car engine and to evacuate the tunnel). The message lines do not include abbreviations. Text is written in capital letters and size is selected in order to take into account legibility distance. A possible size of the text (as it is installed in Norra Länken tunnel in Sweden) is made of a character width of approximately 15 cm. The message is written either in Swedish only or it is constituted by two frames in Swedish and English. The content of the text is a warning message. The warning messages are selected in order to instruct motorists on the action to perform. A set of selected messages are here suggested and they are based on previous experimental research (Nilsson et al., 2009) performed in the Göta tunnel in Sweden where this design has been successfully tested and employed (see Figure 2):

Two-line warning message:
Line 1: "STANNA MOTORN" (Swedish) - "STOP ENGINE" (English)
Line 2: "UTRYM TUNNELN" (Swedish) - "LEAVE TUNNEL" (English)

One-line warning message:
Line 1: "UTRYM TUNNELN" (Swedish) - "LEAVE TUNNEL" (English)

Figure 2. Examples of TIS with a two-line message in amber or a one-line message in white.

It should be noted that the direct translation in English of "Utrym Tunneln" would be "Evacuate Tunnel" rather than "Leave tunnel". Nevertheless, the translation "Leave Tunnel" is used due to space restrictions in the panel. It is in fact recommended to keep the character size always legible, i.e., the character size should not be reduced without an appropriate legibility analysis. It is also recommended to not convey two different messages in the panel (i.e. two different units of information) in different languages. The content of the message "Leave tunnel" is similar to the Swedish version "Utrym Tunneln", thus a similar unit of information is provided.

3.1.3. Flashing effects

Flashing effects can be used for lights or during the display of text messages. As an additional cue, flashing can capture attention to objects in a display better than colours (Thackray and Mark Touchstone, 1991), thus increasing the sensory affordance of the sign. Nilsson (2009) demonstrated the potential benefits of using flashing lights during emergencies.

Different levels of hazard are generally associated with different light flashing rates and modes. In particular, the faster is the flashing rate, the higher is the hazard perceived (Chan and Ng, 2009). Wang et al. (2006) performed a study consisting of a survey and laboratory and field experiments to investigate the optimal flashing effect to display text messages. They found that static or one line flashing messages are the most effective systems and they produce shorter response times. A whole frame flashing message resulted as the worst performing system, i.e. they generate higher response times.

Selected flashing effects

Message lines are static. Zero or four flashing amber lights are provided in the corners of the TISs (see examples in Figure 3). Suggested flash rate of the lights is 1.0 Hz in order to enhance the degree of perceived urgency without creating a flashing effect which may annoy motorists.

Figure 3. Example of layout of amber flashing lights in the corners of a TIS (zero lights on the left image and 4 lights on the right image).

3.1.4. Pictorial symbols

Motorists generally have high accuracy rate when responding to pictorial symbols rather than text only since they present information concisely, thus requiring short search time (Liu, 2005). The comparison between text and pictorial signs demonstrated that the sole use of symbols is advantageous when the observer is familiar with it (Shinar and Vogelzang, 2013). In contrast, when a symbol is replaced by text only, the impact of familiarity becomes irrelevant. Many studies (Koyuncu and Amado, 2008; Liu, 2005; Ou and Liu, 2012; Shinar and Vogelzang, 2013) investigated the combined use of text messages and pictorial symbols. The use of pictorial symbols enhances people capacity in remembering and understanding the content of a message. Written and symbolic stimuli activated both early perceptual and late cognitive processes (Koyuncu and Amado, 2008). This is confirmed by experimental and field studies on traffic signs, e.g., Shinar and Vogelzang (2013) demonstrated that the combination of pictorial symbols and text improved the comprehension and reduce response time. On one hand, this is associated with the concept that the presence of context increases symbol comprehension (Wolff and Wogalter, 1998), thus leading people to have a confirmation on the content of a message in the cases of multiple sources of information. On the other hand, designers should take into account that information overload may potentially reduce the understanding of the message (Wang et al., 2006).

The choice of the symbol to employ should be made in line with the list of international acceptable symbols (International Standards Organization, 2011). Acceptable symbols should have no more than 5 % of critical confusions in line with the definition provided by ANSI (American National Standards Institute, 2011). Critical confusion is used to assess the possible wrong answer to the answer intended to a message and it suggests behaviour that can lead to an accident or injury. The selection of the symbol should be made in line with the type of information provided, i.e. circles are regulatory (generally red and black on white or white on black), triangles are used for warnings (black and yellow or white on red) and squares indicate information (generally white and green or white and blue).

<u>Selected pictorial symbols</u>

Selected pictorial symbols are the standard "do not enter sign", the "warning sign" (International Standards Organization, 2011) and the "emergency exit sign" (AFS, 2008), depending on the information that is intended to be provided (a warning message or information on the emergency exit) (see Figure 4). Pictograms are used in the TIS panel in order to match the adopted colour scheme.

Figure 4. Example of pictogram symbols for TIS.

3.1.5. TIS designs selected for further testing

The design of the TIS is associated with the layout of the panels to be inserted (e.g. the number of panels). The layout under consideration in this document includes the use of two panels (having dimensions corresponding to either 240x170 cm or 240x90 cm) with three intermediate smaller panels (having fixed dimensions corresponding to 90x90 cm). In case of emergency, the smaller panels display red crosses which are used to encourage tunnel occupants to stop their vehicles.

A set of TIS designs have been selected for investigation based on the review presented in this section. They investigate the combination of different systems (colour scheme, written message design, flashing effects, pictorial symbols) and present different characteristics.

The selected TIS designs are described in Table 1 and shown in Figure 5a-5b. Colour scheme for the background and written message is black/amber, or black/white and black/red (the literature review revealed that these colour schemes are the one which may possibly perform better). The written message is either made of 1 line or 2 lines. Language is either Swedish or Swedish and English. Text is fixed (i.e. flashing effects on the text are excluded due to the discussion presented in the literature review). The number of flashing lights in each panel is zero or four. Pictorial symbols are the “warning sign”, the “do not enter sign”, the “emergency exit sign” (the colours of the pictograms may be modified to keep a two-colour scheme in the panel) or no sign is provided at all.

Table 1. Selected combinations of characteristics of the TIS and resulting designs.

TIS Design name	Colour scheme	Written message (lines per panel)	Language	Flashing lights (per panel)	Pictorial symbol	Panel sizes (cm)
1	Black/amber	0+2	Swedish	4+4	warning	240x170 and 240x90
2	Black/amber	2+2	English/ Swedish	4+4	/	240x90 and 240x90
3	Black/amber	0+2	Swedish	0+0	warning	240x170 and 240x90
4	Black/amber	0+2	Swedish	2+2	warning	240x90 and 240x90
5	Black/green/ amber	1+1	Swedish	4+4	/	240x90 and 240x90
6	Black/amber	2+2	Swedish/Swedish	4+4	/	240x90 and 240x90
7	Black/amber	0+2	Swedish	0+4	Emergency exit	240x170 and 240x90
8	Black/white/ Amber	1+1	Swedish	0+4	Emergency exit	240x170 and 240x90
9	Black/red/ amber	0+2	Swedish	4+4	Do not enter	240x170 and 240x90
10	Black/red	0+2	Swedish	4+4	Do not enter	240x170 and 240x90
11	Black/amber	1+1	Swedish	4+4	warning	240x170 and 240x90

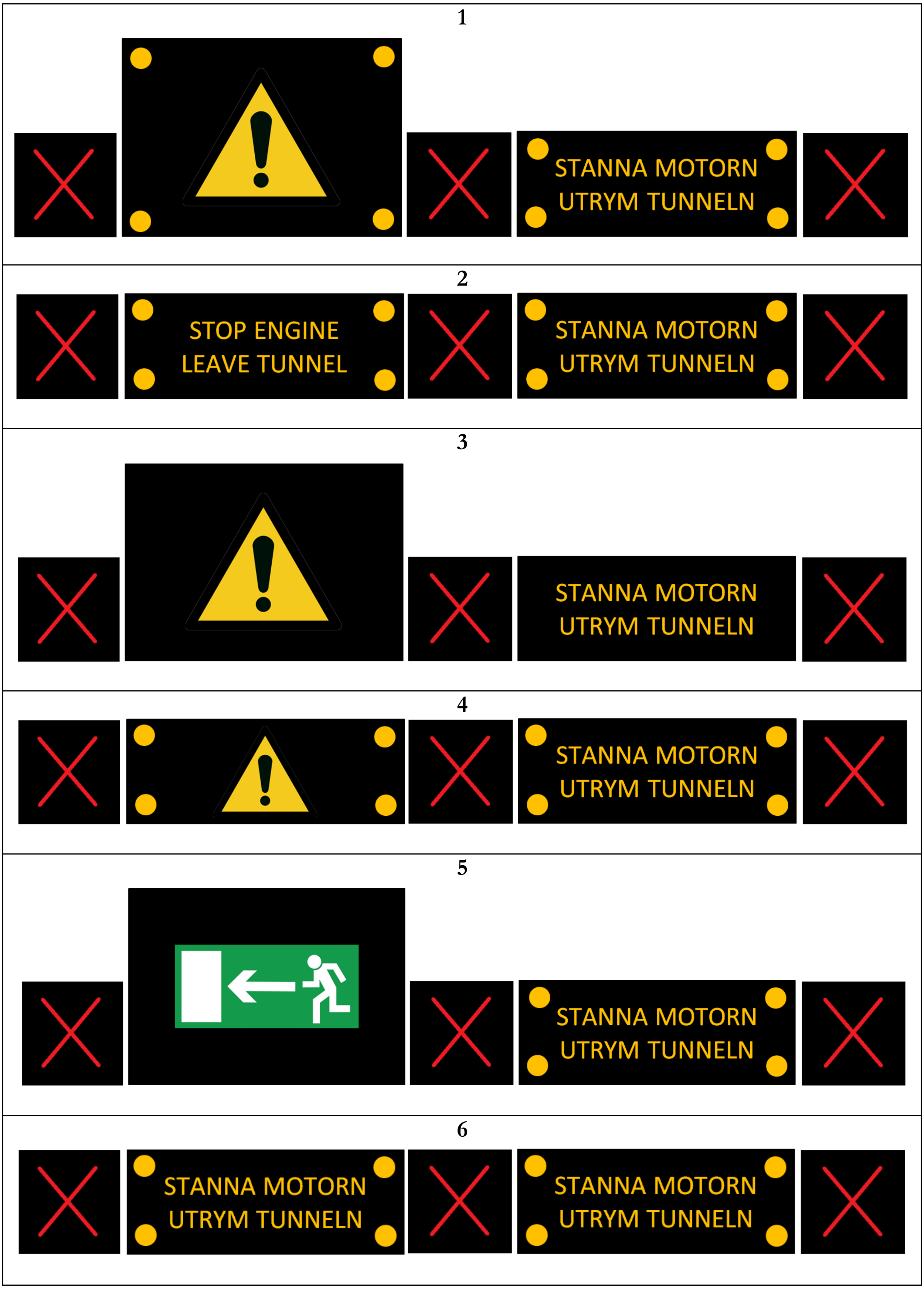


Figure 5a. Schematic representation of the preliminary list of TIS designs (1-6).

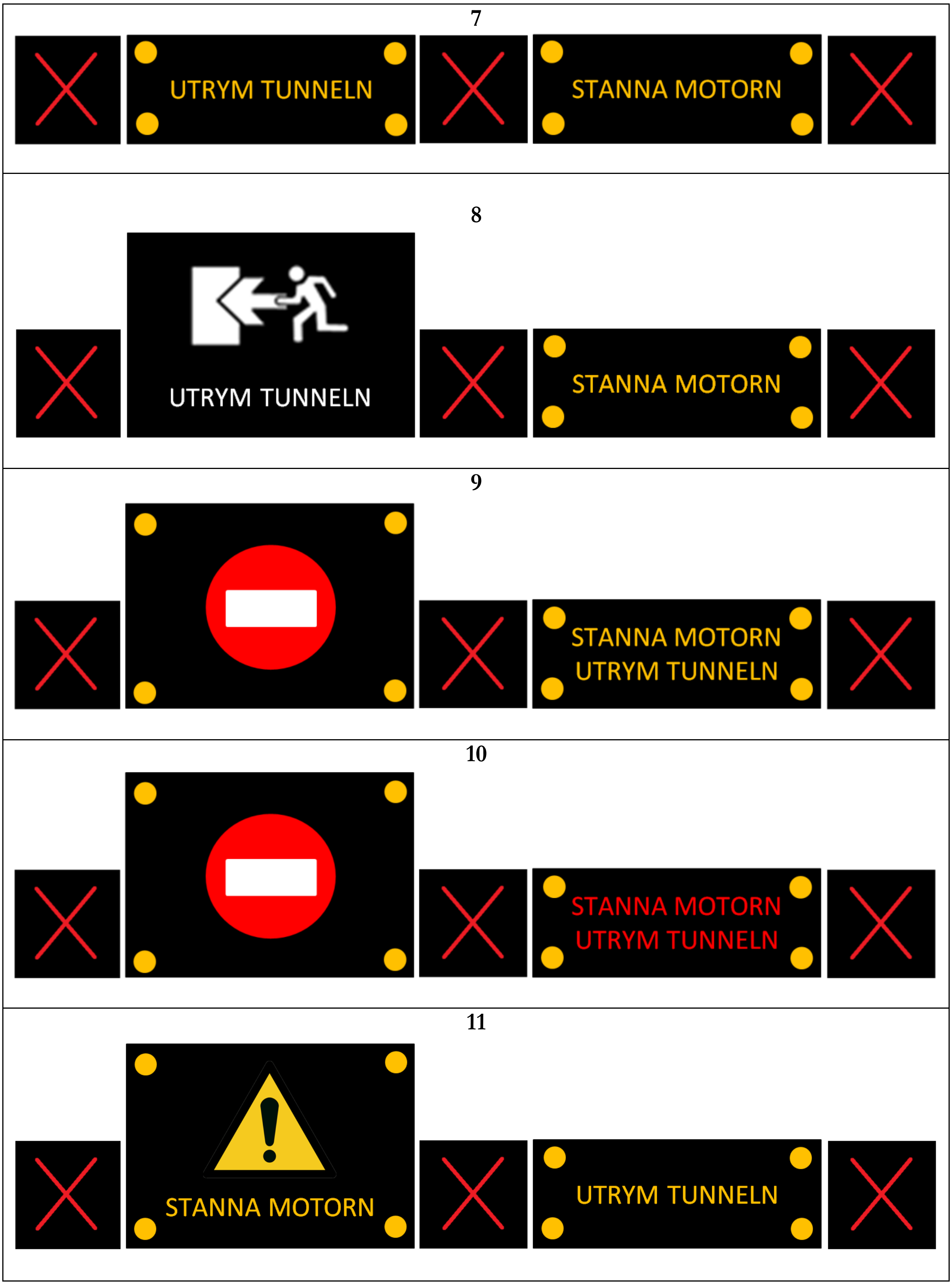


Figure 5b. Schematic representation of the preliminary list of TIS designs (7-11).

3.2. Preliminary analysis of TIS designs

The Theory of Affordances is here used to discard the designs which may potentially not perform well in terms of their capability to instruct people on the action to perform in case of an emergency. The remaining designs will be tested during a dedicated experimental study. The affordances are evaluated in this case in relation to a benchmark design of the TIS (see Figure 6).

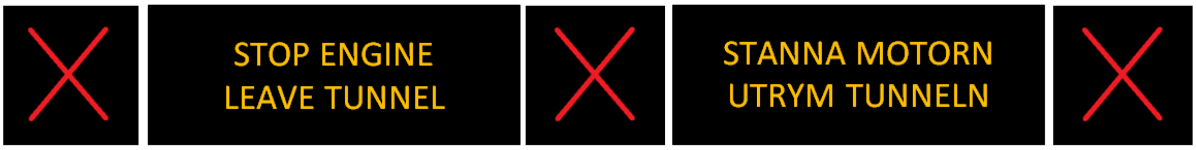


Figure 6. Benchmark design of the TIS used for the evaluation of the 11 TIS designs using the Theory of Affordance.

3.2.1. Sensory affordance

Sensory affordance is determined in TISs by their capability of attracting the attention of the motorists and their subsequent ability in seeing the message provided. This is associated with the location (which is constant in this study) and size of the panels (large or small panel on the side of the emergency exit), the colour in use and the type of code displayed in the sign (text, pictorial symbols, and flashing lights) and its characteristics. The literature review presented in this section highlighted that people tend to perceive faster amber than other colours in the case of written messages in TIS, thus the use of red and white colour (e.g., TIS design 8 and TIS design 10) may produce a lower sensory affordance. The use of flashing lights is deemed to contribute at capturing the attention of the motorists. The use of panels of bigger size on the size of the emergency exit (240x170 cm) is deemed to increase sensory affordance, although experimental tests are needed to evaluate the impact of the size of the panel. As described in the review, double-line messages generally lead to a faster reading if compared with single line messages (TIS designs 7, 8 and 11). Sensory affordance is deemed to be very important for the case of TIS, given the fact that motorists may need to notice and distinguish the sign in a relatively short time. The list of the factors influencing sensory affordance for each design is presented in Table 2a-2b.

Table 2a. Possible factors which may contribute to increase or decrease sensory affordance ("+" indicates a factor which increases affordance, while "-" indicates a factor which decreases it) for TIS designs 1-8.

TIS design	Sensory affordance
1	+ Warning sign makes the TIS easier to be noticed/discovered + Warning sign makes the TIS easier to be distinguished + Eight amber flashing lights makes the TIS easier to be noticed/discovered + Bigger size of one panel makes the TIS easier to be noticed/discovered + Bigger size of one panel makes the TIS easier to be distinguished
2	+ Eight amber flashing lights makes the TIS easier to be noticed/discovered
3	+ Warning sign makes the TIS easier to be noticed/discovered + Warning sign makes the TIS easier to be distinguished + Bigger size of one panel makes the TIS easier to be noticed/discovered + Bigger size of one panel makes the TIS easier to be distinguished
4	+ Warning sign makes the TIS easier to be noticed/discovered + Warning sign makes the TIS easier to be distinguished + Eight amber flashing lights makes the TIS easier to be noticed/discovered - Reduced size of the pictogram makes the TIS harder to be noticed/discovered - Reduced size of the pictogram makes the TIS harder to be distinguished
5	+ Emergency exit pictogram makes the TIS easier to be noticed/discovered + Emergency exit pictogram makes the TIS easier to be distinguished + Flashing lights in one panel makes that panel easier to be noticed/discovered - Only one panel with flashing lights makes the other panel not easier to be noticed/discovered + Bigger size of one panel makes the TIS easier to be noticed/discovered + Bigger size of one panel makes the TIS easier to be distinguished
6	+ Eight amber flashing lights makes the TIS easier to be noticed/discovered
7	+ Eight amber flashing lights makes the TIS easier to be noticed/discovered - One-line texts makes the text harder to be noticed/discovered - One-line texts makes the text harder to be distinguished
8	+ Emergency exit pictogram makes the TIS easier to be noticed/discovered + Emergency exit pictogram makes the TIS easier to be distinguished + Flashing lights in one panel makes that panel easier to be noticed/discovered - Only one panel with flashing lights makes the other panel not easier to be noticed/discovered + Bigger size of one panel makes the TIS easier to be noticed/discovered + Bigger size of one panel makes the TIS easier to be distinguished - White colour in the written message makes the TIS harder to be noticed/discovered - White colour in the written message makes the TIS harder to be distinguished - Reduced size of the pictogram makes the TIS harder to be noticed/discovered - Reduced size of the pictogram makes the TIS harder to be distinguished - One-line texts makes the text harder to be noticed/discovered - One-line texts makes the text harder to be distinguished

Table 2b. Possible factors which may contribute to increase or decrease sensory affordance ("+" indicates a factor which increases affordance, while "-" indicates a factor which decreases it) for TIS designs 9-11.

TIS design	Sensory affordance
9	+ "Do not enter" sign makes the TIS easier to be noticed/discovered + "Do not enter" sign makes the TIS easier to be distinguished + Eight amber flashing lights makes the TIS easier to be noticed/discovered + Bigger size of one panel makes the TIS easier to be noticed/discovered + Bigger size of one panel makes the TIS easier to be distinguished
10	+ "Do not enter" makes the TIS easier to be noticed/discovered + "Do not enter" sign makes the TIS easier to be distinguished + Eight amber flashing lights makes the TIS easier to be noticed/discovered + Bigger size of one panel makes the TIS easier to be noticed/discovered + Bigger size of one panel makes the TIS easier to be distinguished - Red colour in the written message makes the TIS harder to be discovered/noticed - Red colour in the written message makes the TIS harder to be distinguished
11	+ Warning sign makes the TIS easier to be noticed/discovered + Warning sign makes the TIS easier to be distinguished + Eight amber flashing lights makes the TIS easier to be noticed/discovered + Bigger size of one panel makes the TIS easier to be noticed/discovered + Bigger size of one panel makes the TIS easier to be distinguished - One-line texts makes the text harder to be noticed/discovered - One-line texts makes the text harder to be distinguished - Reduced size of the pictogram makes the TIS harder to be noticed/discovered - Reduced size of the pictogram makes the TIS harder to be distinguished

3.2.2. Cognitive affordance

Cognitive affordance in the case of TIS is associated with the effectiveness of the panel in providing information that motorists can understand. This is dependent on the code employed (text, pictorial symbols, flashing lights) and the written message design and their combination. The use of pictorial symbols of different colours than the text (TIS design 5, 8, and 9) is deemed to create confusion in the motorists and it may decrease cognitive affordance. This solution is not recommended, but experimental tests are needed to verify if this negative effect can be balanced by the use of an effective pictorial symbol (e.g. TIS design 5). The use of pictorial symbols in an unusual colour may decrease cognitive affordance (e.g. TIS design 8). Since the information to be transmitted concerns an emergency, it is deemed that the use of a white colour scheme for the text (TIS design 8) may decrease cognitive affordance on the message if compared with the use of amber or red, i.e. motorists may not perceive the emergency and the urgency of the situation. The signs are intended to instruct the users on the actions to perform. In this case, the two required actions to perform are to turn off the engine and to reach an emergency exit on foot. For this reason, the two-line messages should include specific instructions on the actions to perform. For instance, the use of the single unit of information "Utrym tunneln" may decrease cognitive affordance and be mis-interpreted since motorists are not specifically instructed to abandon their cars and perform their evacuation on foot. For this reason, all selected TIS include both instructions on the actions to perform. The use of written messages in different languages may affect cognitive affordance in relation to the expected type of population involved (i.e. if the majority of the population involve Swedish speakers).

As described in the review, the combined use of pictorial symbols and flashing lights with text may increase cognitive affordance. Nevertheless, there is the risk that too many stimuli can generate confusion to the motorists. For this reason, there is the need to experimentally assess the optimal combination of systems in order to increase the understanding on the effectiveness of the information provided by TIS. A summary of the factors influencing functional affordance is presented in Table 3a-3b.

Table 3a. Possible factors which may contribute to increase or decrease cognitive affordance ("+" indicates a factor which increases affordance, while "-" indicates a factor which decreases it) for TIS designs 1-7.

TIS design	Cognitive affordance
1	+ Familiar pictorial symbol better conveys warning + Combination of pictogram and flashing lights increases message understanding + Eight amber flashing lights better communicate warning
2	+ Non-Swedish speakers can better understand the message + Eight amber flashing lights better communicate warning - Two different messages in two languages in the panels create confusion to non-English speakers
3	+ Familiar pictorial symbol better conveys warning + Combination of pictogram and flashing lights increases message understanding
4	+ Familiar pictorial symbol better conveys warning + Combination of pictogram and flashing lights increases message understanding + Eight amber flashing lights better communicate warning
5	+ Familiar pictorial symbol better conveys safety instructions + Combination of pictogram and flashing lights increases message understanding + Eight amber flashing lights better communicate warning + Green is a familiar colour to communicate safety message - Only one panel with flashing lights decreases message understanding - The use of two different colours in the panels (pictogram is green while written message is amber) creates confusion - The use of two type of units of information in the panels (safety and warning) creates confusion
6	+ Eight amber flashing lights better communicate warning + The repetition of the same warning message in two different panels better communicate warning
7	+ Eight amber flashing lights better communicate warning - Two different written messages in the two panels creates confusion

Table 3b. Possible factors which may contribute to increase or decrease cognitive affordance ("+" indicates a factor which increases affordance, while "-" indicates a factor which decreases it) for TIS designs 8-11.

TIS design	Cognitive affordance
8	+ Combination of pictogram and flashing lights increases message understanding + Eight amber flashing lights better communicate warning - Only one panel with flashing lights decreases message understanding - White is not a familiar colour to communicate safety message and reduces message understanding - Two different written messages in the two panels creates confusion - The use of two different colours in the panels (pictogram is white, while written message is amber) creates confusion - The use of two type of units of information in the panels (safety and warning) creates confusion
9	+ Eight amber flashing lights better communicate warning + Familiar pictorial symbol better conveys danger - Combination of pictogram and flashing lights conveying two different units of information (danger and warning) decreases message understanding - The use of a "do not enter" sign is contradictory with the message of leaving the tunnel - The use of two different colours in the two panels (pictogram is red and white, while written message is amber) creates confusion - The use of two different colours within a panel (text or signs are red while flashing lights are amber) creates confusion
10	+ Eight amber flashing lights better communicate warning + Familiar pictorial symbol better conveys danger - Combination of pictogram and flashing lights conveying two different units of information (danger and warning) decreases message understanding - The use of a "do not enter" sign is contradictory with the message of leaving the tunnel - The use of two different colours within each panel (text or signs are red while flashing lights are amber) creates confusion
11	+ Familiar pictorial symbol better conveys warning + Combination of pictogram and flashing lights increases message understanding + Eight amber flashing lights better communicate warning - Location of the warning pictogram and message to leave the tunnel on the left panel decreases message understanding (since motorists read panels from left to right)

3.2.3. Physical affordance

Physical affordance supports the user physically performing an action. The TIS is a sensory system which does not require a physical interaction with the object under consideration. For this reason, physical affordance is deemed to be not applicable during the analysis of TIS through the Theory of Affordances.

3.2.4. Functional affordance

Functional affordance is associated with the goals of the motorists in the tunnel. Main goals of the tunnel occupants include reaching a safe place overcoming possible property attachment (i.e. the reluctance to leave the vehicle) and social influence. All systems under consideration are designed in line with the same goals. For this reason, it is argued that functional affordance can be directly derived as a consequence of the factors affecting the other affordances (sensory and cognitive in this case). Those factors can be read in previous Table 2a-2b and Table 3a-3b. High scores in functional affordance are resulting from a powerful combination of the other affordances. If a system fails in terms of one of the affordances, the functional affordance will also be low as a result of the failing of that affordance.

3.2.5. Qualitative affordance scores

A summary of the qualitative evaluation of the TIS using the Theory of Affordances is presented in Table 4.

Table 4. Qualitative evaluation of the TIS in relation to the Theory of Affordance.

TIS design	Sensory affordance	Cognitive affordance	Physical affordance	Functional affordance
1	High	Medium	Not applicable	Medium/High
2	Medium	Medium	Not applicable	Medium
3	Medium	Medium	Not applicable	Medium
4	Medium	Medium	Not applicable	Medium
5	Medium	High	Not applicable	Medium/High
6	Medium	Medium	Not applicable	Medium
7	Low	Low	Not applicable	Low
8	Low	Low	Not applicable	Low
9	High	Low	Not applicable	Low
10	Medium	Low	Not applicable	Low
11	Low	High	Not applicable	Low

The TIS designs which present either a low score in sensory, cognitive or functional affordance have been excluded from further experimental evaluation. In conclusion, the use of the Theory of Affordances permitted the exclusion of five TIS designs, namely TIS design 7, 8, 9, 10 and 11. The TIS designs selected for dedicated experimental research are therefore TIS design 1, 2, 3, 4, 5 and 6.

3.3. Experimental testing of TIS designs

The analysis of TIS designs using the Theory of Affordances permitted the selection of six possible designs for the TIS. The selected designs are tested experimentally in order to validate the results of the analysis, give recommendations on appropriate TIS design and select the best designs. The designs under consideration are presented in Figure 7.

Figure 7. TIS designs selected for experimental testing.

3.3.1. Method

An affordance-based questionnaire has been administered to test participants. The designs are evaluated experimentally performing dedicated pairwise comparisons of designs which permit the testing of different variables. Test participants were required to sit in a room where two screens were made available, each one presenting one TIS design. The variables under consideration are (see Table 5):

- Use of pictorial symbols vs written text (Swedish and English)
- Type of pictorial symbol
- Size of the panel on the side of the emergency exit (small or large)
- Use of flashing lights
- Use of pictorial symbols vs written text (Swedish)

Table 5. Summary of the pairwise comparisons of TIS designs.

Test	Comparison of TIS design	Variable under consideration
A	4 vs 6	Use of pictorial symbols vs written text (Swedish)
B	5 vs 1	Type of pictorial symbol/flashing
C	4 vs 1	Size of the panel on the side of the emergency exits
D	1 vs 3	Use of flashing lights
E	4 vs 2	Use of pictorial symbols vs written text (Swedish and English)

Test A

This comparison is performed in order to investigate the impact of the use of written text (in Swedish) only vs the combined use of text and pictograms in the two panels (see Figure 8). The analysis is performed by comparing TIS design 6 and TIS design 4. The test permits also the assessment of the impact of the use of Swedish language only or the use of pictorial symbols.

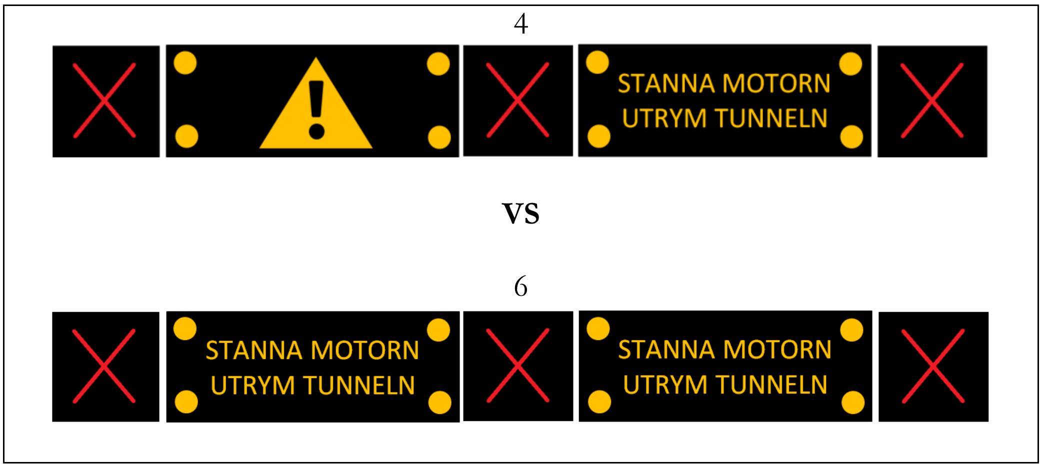


Figure 8. Comparison of TIS design 2 vs TIS design 4.

Test B

This comparison is performed in order to investigate the use of different pictorial symbols (the warning symbol and the emergency exit symbol), see Figure 9. Flashing lights are not available in the panel with the emergency exit sign in order to avoid contradictory messages (flashing lights communicate warning while the emergency exit signs indicate safety). The analysis is performed by comparing TIS design 1 and TIS design 5.

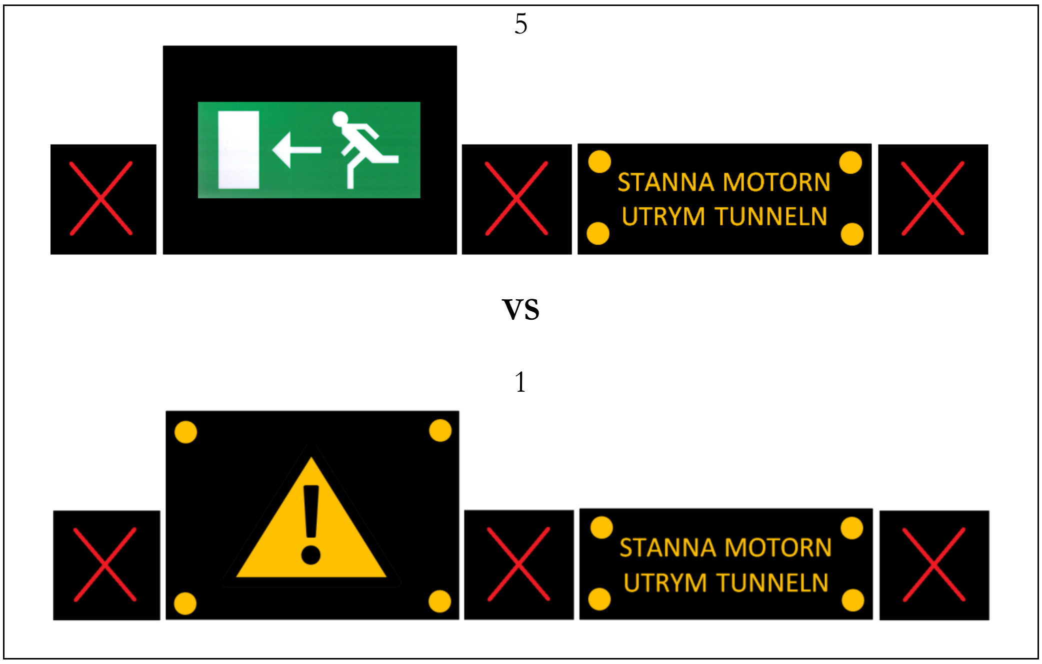


Figure 9. Comparison of TIS design 1 vs TIS design 5.

Test C

This comparison is performed in order to investigate the impact of the size of the panel on the side of the emergency exits (large or small size) and the subsequent size of the pictogram (see Figure 10). The analysis is performed by comparing TIS design 1 and TIS design 4.

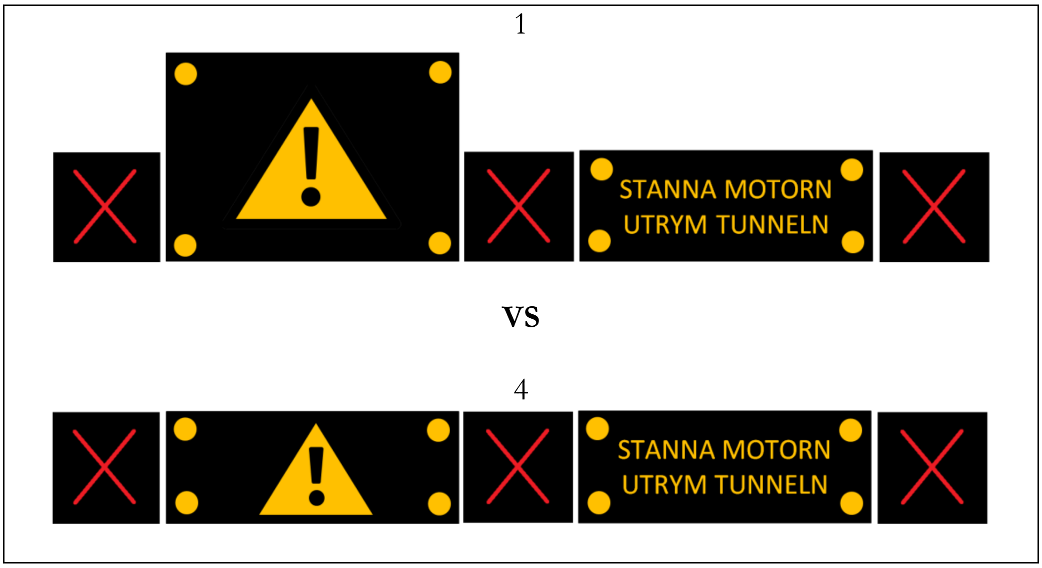


Figure 10. Comparison of TIS design 1 vs TIS design 4.

Test D

This comparison is performed in order to investigate the impact of the use of flashing lights. The analysis is performed by comparing TIS design 1 and TIS design 3 (see Figure 11).

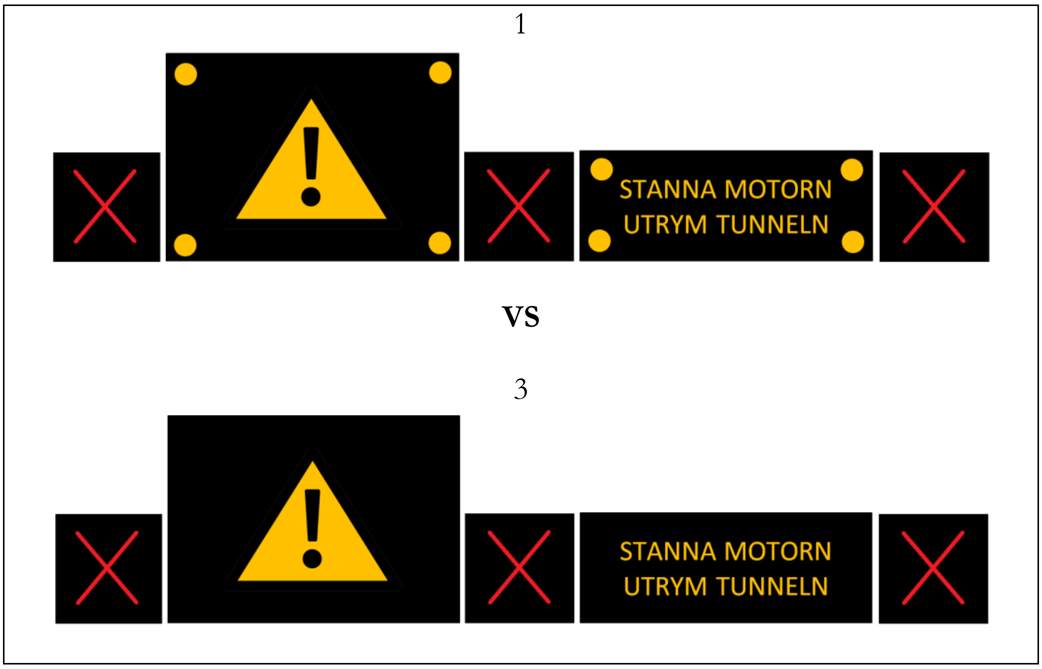


Figure 11. Comparison of TIS design 1 vs TIS design 3.

Test E

This comparison is performed in order to investigate the impact of the use of written text (in Swedish and English) only vs the combined use of text and pictograms in the two panels (see Figure 12). The analysis is performed by comparing TIS design 2 and TIS design 4. The test permits also the assessment of the impact of the use of the combination of text in English and Swedish vs the use of text and pictograms.

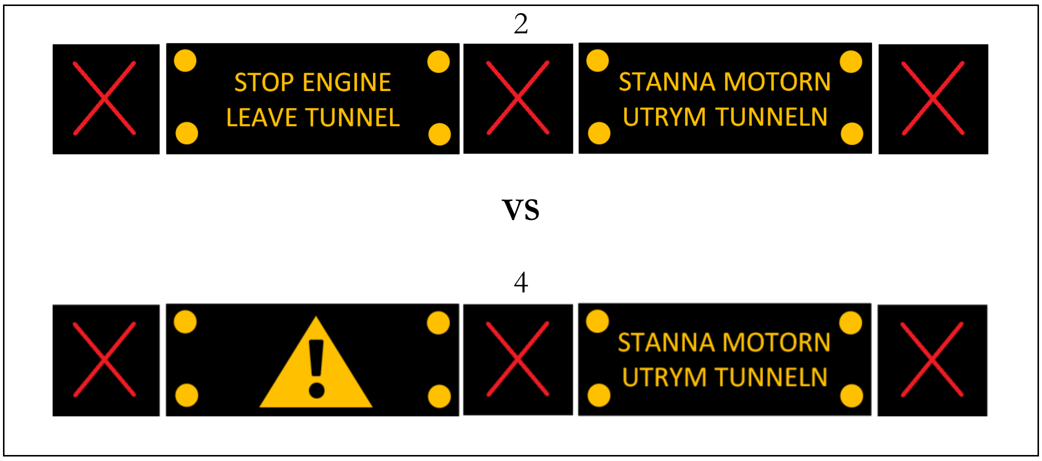


Figure 12. Comparison of TIS design 2 vs TIS design 4.

The pairwise comparison of designs is made using a questionnaire based on the Theory of the affordance. The questionnaire is presented in Appendix 2.

3.3.2. The questionnaire

The questionnaire includes five questions investigating the affordances associated with different TIS systems (see Appendix 2). In the first four questions, test participants can choose one of the two TIS systems or state that the two systems are equally performing. In the final question, test participants must select only one of the two configurations. Test participants are also requested to justify their choice with an open text.

The first two questions deals with sensory affordance. The first question investigates the capability of the sign of capturing the attention of the participants:

1) *Which of the two configurations is the easiest to notice?*

The second question asks the participants if the TIS system is discernible and the information can be distinguished:

2) *Which of the two configurations is the easiest to distinguish details?*

The third and fourth questions investigated cognitive affordance in accordance to the expected goals of the TIS systems:

3) *Which of the two configurations convey best the message that you should leave the car?*
4) *Which of the two configurations convey best the message that you should use an emergency exit?*

The fifth question is the final question (functional affordance) in which the test participants are required to select the best TIS system:

5) *Which of the two configurations offer overall the best support for your evacuation?*

The final part of the questionnaire includes general background questions such as age, nationality, gender, spoken and read languages, country of residence, colour blindness, profession, driving license, average use of tunnels, and previous evacuation experiences in tunnels (see Appendix 2).

3.3.3. Participants

A total of 62 participants have been recruited for the questionnaire study. Participants were recruited among students and staff at Lund University, in Lund, Sweden. The means of recruitment and participants' characteristics are presented in the present section.

Approximately two weeks before the experiment, information about the study was sent through a University mailing list to employees at Lund University. Participants were also recruited among students by contacting them at the end of lectures at the university. General information about the experiments was provided (e.g., possible dates, location and duration of the experiments, etc.) An example of the information provided is presented in Appendix 1. People interested to participate at the experiments were given the possibility to express their interest by providing their name and phone number. Students at fire protection engineering program at Lund University were excluded from the recruitment process in order to ensure that the sample does not include participants fully aware of the research conducted. In order to ensure that the sample was representative of the Swedish population, only participants living in Sweden were recruited. One day before the corresponding experimental trial, an SMS was sent to the test participants to remind them about the experiment. A total of 62 participants were recruited. Participants were split in four different experimental trials where the order of the comparisons was randomized in order to avoid systematic errors in the evaluation of the TIS systems.

The first two trials were conducted in the A:B room in the Architectural building at Lund University, Sweden, respectively on the 22nd and 27th of November 2013. On 4th and 5th of December trials 3 and 4 respectively took place. Trials 3 and 4 were conducted in the EC3:109 room at the Economy building at Lund University, Sweden. Table 6 shows the number of participants for each trial, and the day and the room were the trial took place.

Table 6. General information about the questionnaire study trials.

Trial number	***Room***	***Day***	***Number of participants***
Trial 1	A:B	*22nd of November*	*21*
Trial 2	A:B	*27th of November*	*18*
Trial 3	EC3:109	*4th of December*	*11*
Trial 4	EC3:109	*5th of December*	*12*

A total of sixty-two participants took part in the experiment (34 male and 28 female). Test participants' age ranged from 18 to 54 years old (average=24.3 years and standard deviation=6.8 years). Fifty eight of the sixty-two participants (93.5%) were of Swedish nationality, two participants had double citizenship (Swedish and another citizenship) and 2 participants were not Swedish. All participants were Swedish native speakers, and 60 out 62 participants were able to read and understand English as well. The sample was mainly made of students (85.5% of the participants), but in order to ensure that the results were not biased by the presence of only one type of population, the rest of sample includes people of different ages and professions (e.g. university employees, lecturers, housekeepers, etc.). Participants did not declare to have sight impairments with the exception of one participant who declared to have difficulties in distinguishing colours. Most of the participants (93.5%) did not have previous experiences concerning tunnel evacuations. Four participants (6.5%) declared to have previous experiences on tunnel evacuation such as experiencing the traffic being stopped while inside the car in a tunnel due to an accident (two participants) and two cases of full evacuation of the tunnel (one case including visible smoke from the car involved in the accident). Most of the participants (89%) had a driving license. The majority of the participants were not very frequent tunnel users, with the most common use being once per year (46.8%), followed by less than once per year (27.4%) and once per month (22.6%). This is deemed to be a conservative assumption in the sample since tunnel users are not deemed to have large experience about tunnel evacuations.

3.3.4. Procedure

Approximately three weeks before the experiment, pilot testing has been conducted in order to ensure that the questions proposed to the participants were correctly understood and interpreted. The day of each experiment, participants were gathered in the room with the two screens. Prior to start the tests, participants were told to take different seats in the room where questionnaires were made available (see Figure 13).

Figure 13. The picture shows the position of the questionnaires in one of the rooms where the study took place.

Introductory information about the experiments was given by one of the researchers. Test participants were then told to be in a stopped car during a hypothetical tunnel evacuation scenario (see Figure 14 for an example of the visualization of the two screens in the room). Once participants agreed to have fully understood the instruction, lights in the room were switched off. The TIS designs were showed to the test participants who were asked to fill out the questionnaire and evaluate the pairs (A and B) of TIS designs. TISs were showed blank during the description of the hypothetical scenario. Once all information was provided, a sound alarm went off (the alarm was the F_SAW alarm based on British Standards (2013)), and the trial began. Appendix 2 presents the information provided to the test participants. The hypothetical view from the car was created using the Virtual Reality software Unity3D.

Figure 14. Example of visualization of the hypothetical tunnel evacuation scenario in the tunnel.

3.3.5. Data collection

After the participants evaluated all five pairs of TIS designs through the questionnaire, they were thanked and they were given a cinema ticket for their participation. The answers provided by the test participants were copied in spreadsheets in order to facilitate their analysis.

3.3.6. Results

Statistical testing has been performed in order to test the null hypothesis that a certain element in the design of the Traffic Information Sign (TIS) affects the preference of one sign over another, i.e. the proportion of participants selecting a TIS is not equal ($p_0 \neq 0.5$).

Repeated exact binomial tests with Bonferroni corrections have been performed to test this hypothesis for each comparison. Binomial tests are exact tests of statistical significance of deviations from a theoretically expected distribution of observations in two categories. In the present case, the null hypothesis is that two categories are equally likely to occur ($p_0=0.5$), i.e. there is no preference by the participants of a sign over another.

Since multiple comparisons are performed, a Bonferroni correction has been employed. This is the most conservative method to control the family-wise error rate (i.e. the probability of making one or more false discoveries when performing multiple hypotheses tests). The Bonferroni correction assumes the achievement of a significance level for the whole family of tests equal to (at most) α, can be obtained by testing each of the individual tests at a significance level α/n. In the present case, $n=5$, $\alpha=0.05$, which corresponds to a corrected significance level $\alpha_c=0.01$.

A summary of the results of the affordance-based questionnaire is provided in Table 7. A summary of the results of is provided in Table 4. It should be noted that the number of responses considered for binomial testing for each questions are different because participants stating (in Q1, Q2, Q3 and Q4) that there were no differences among the designs were removed.

Table 7. Summary of the results of the affordance-based questionnaire. n is frequency of a chosen design, % is the percentage of chosen design, p is the probability. Q1 and Q2 are the questions regarding sensory affordances, Q3 and Q4 refers to cognitive affordances.

	Q1			Q2			Q3			Q4			Q5		
	n	%	*p*	n	%	*p*	n	%	*p*	n	%	*p*	n	%	*p*
TEST A															
Design 4	35	90	0.000	26	79	0.001	15	44	0.608	7	54	1.000	29	71	0.012
Design 6	4	10		7	21		19	56		6	46		12	29	
TEST B															
Design 5	13	25	0.010	19	68	0.087	47	84	0.000	59	97	0.000	50	81	0.000
Design 1	38	75		9	32		9	16		2	3		12	19	
TEST C															
Design 4	1	2	0.000	11	31	0.041	5	31	0.210	4	57	1.000	9	15	0.000
Design 1	58	98		24	69		11	69		3	43		51	85	
TEST D															
Design 3	0	0	0.000	10	34	0.136	0	0	0.000	0	0	0.002	0	0	0.000
Design 1	62	100		19	66		25	100		10	100		62	100	
TEST E															
Design 4	49	88	0.000	30	68	0.023	13	25	0.000	7	35	0.263	21	34	0.015
Design 2	7	13		14	32		39	75		13	65		41	66	

Conditional probabilities have been calculated in order to analyse the individual answers to the questions about sensory (Q1-Q2) and cognitive (Q3-Q4) affordances and their relation to the final choice of the TIS design (i.e., Q5), (see Figure 14). This analysis is conducted for all tests A-E. This has been done by relating the answers in Q1-Q4 with the final answers in Q5 and calculating the percentages of the corresponding conditional probabilities. The matching between answers in Q1-Q4 and Q5 can then be analysed.

Three different conditions are possible. In the first case, there is agreement between the answers to Q1, Q2, Q3 or Q4 and the final preference of the design expressed in Q5; i.e., respondents choose consistently one of the two system designs (A or B). The second case is the disagreement between the design selected when answering to Q1, Q2, Q3 or Q4 and the final choice of the preferred design expressed in Q5. The third case relates to the cases in which respondents claim that designs are equally performing when answering to Q1, Q2, Q3 or Q4 and eventually choose one of the two systems when answering to Q5. For instance, the "Q1→Q5" label in the x axis in Figure 14 is used to indicate the case of the answers to Q5 in relation to the answer to Q1 (which may agree, disagree or have an equal stated preference in Q1). The higher is the percentage displayed in Figure 14, the higher is the observed frequency of conditional probabilities representing the answers in Q1-Q4 in relation to the final choice of the TIS design (Q5).

Test A shows that the higher matching of answers for the conditional probabilities is observed for sensory affordance. In fact, the highest observed agreements are Q1→Q5 (73%), and Q2→Q5 (68%). This indicates a stronger agreement between sensory affordance and the final choice of the TIS design in comparison with cognitive affordance. A similar trend is observed in Test C (e.g., the agreement for Q1→Q5 is 87%) and Test D where perfect agreement is found for the answer to Q1 and to Q5 (100% of participants answered B in Q5 if they answered B in Q1). In contrast, high agreement of answers are observed for Q3→Q5 (79%) and Q4→Q5 (85%) in TEST B, as well as answers Q3→Q5 (76%) in TEST E. In those cases, cognitive affordance seems to have a higher agreement with the final choice of the TIS design.

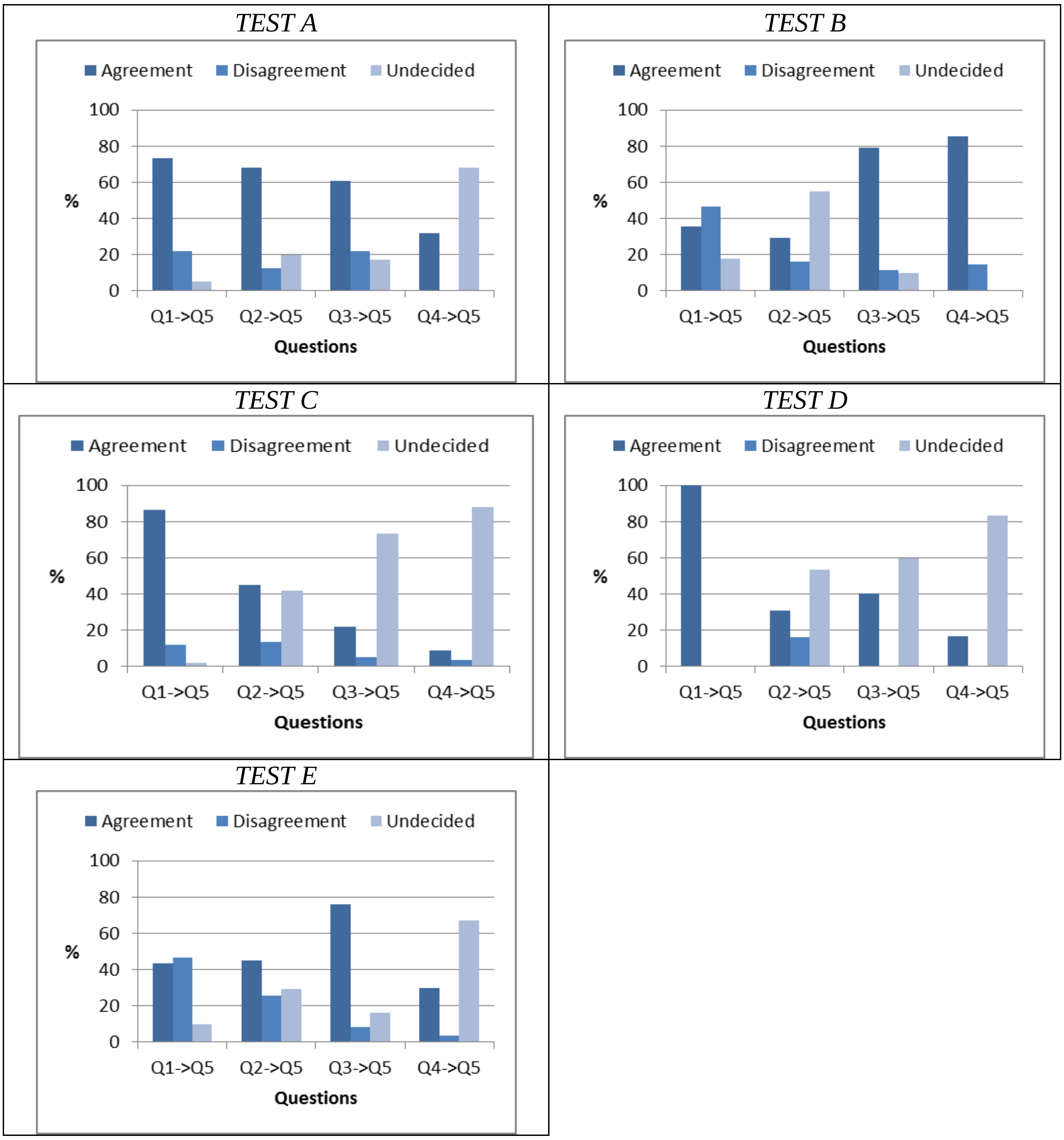


Figure 15.Conditional probabilities of answers to Q5 in relation to the answers to the other questions (Q1-Q4).

3.3.7. Discussion

Exact two-tailed binomial tests with Bonferroni corrections indicated three strong trends:

- TEST B: The "emergency exit" pictorial symbol is preferred over the warning symbol ($p=0.00$ for Q5)
- TEST C: Bigger size of the panels are preferred over signs with smaller size ($p=0.00$ for Q5)
- TEST D: Signs including the use of flashing lights are preferred over signs without flashing lights ($p=0.00$ for Q5)

In general, conditional probabilities (see Figure 15) seem to show that sensory or cognitive affordance may have different impacts on functional affordance and the subsequent final choice of a TIS design in relation to the comparison under consideration. Results indicate trends in the impact of certain sensory and cognitive features. The "emergency exit" pictogram (TIS design 5) generates significantly higher cognitive affordance if compared with the warning pictogram (TIS design 1) and this affects the final choice of a TIS design over another. The sign with warning symbols (TIS design 1) seems to generate higher sensory affordance if compared with the emergency exit pictogram (significant differences are observed only for Q1). This is deemed to be driven by the use of flashing lights in TIS design 5 and the use of amber rather than green in the pictogram.

The use of a bigger size of the panels (TIS design 1) is preferred over a smaller size (TIS design 4) because of the significantly higher sensory affordances they generate (Q1 in Test C shows a clear preference of the bigger panel).

If the pictogram employed is constant (TEST D), signs including flashing lights (TIS design 1) are preferred over signs without flashing lights (TIS design 3). Significant differences in preference for the TIS system including flashing lights have been found for both sensory and cognitive affordance (Q1, Q3 and Q4).

Frequencies of preferences show that participants indicates a preference of the small pictorial symbol over the text in Swedish (69% of the participants selected the TIS with pictorial symbol) and a preference of the text in English and Swedish over the small pictorial symbol (67% of the participants selected the TIS with text in English and Swedish). Exact binomial tests with Bonferroni corrections indicated no significant statistical differences between the use of small pictorial symbols vs text in Swedish ($p=0.015$ for Q5 in Test E) or Swedish and English ($p=0.012$ for Q5 in Test A). The use of pictorial symbol generate higher sensory affordances (see Q1 and Q2 in TEST A and TEST E), but this benefit seems to be compensated by the higher cognitive affordances generated by the presence of text. For instance participants seems to prefer TIS design 2 (including text in Swedish and English) over TIS design 2 (including the use of a pictorial symbol in the left panel) in terms of cognitive affordance (see the results of binomial testing for Q3) and this has a strong correlation on their final choice of the sign. It is argued that this may be associated with the sample under consideration (mostly composed by Swedish and

English speakers). Further testing is necessary to address this issue in relation to the type of population involved.

To summarize, the present work allows presenting the following list of findings and recommendations on TIS design for road tunnel evacuation:

1) The combined use of one sign with text and another panel with a pictorial symbol is recommended
2) The "emergency exit" symbol in green is preferred over the "warning" symbol
3) The recommended colour for the written text in the panels is amber
4) The use of flashing lights is recommended in panels with warning messages
5) An increased size of the panels is recommended
6) The amount of information in the sign should be kept as small as possible
7) Information in the sign should be properly separated

3.3.8. Ethical considerations

Both oral and written information were given to the participants about their right to abort the tests at any time by giving a signal to one of the researchers in the laboratory. Written description of the experiment was given to the participants, including information on handling and use of data. Before the start of the experiments, during the preparation step, each participant received again oral information about their rights. Participants received a compensation for their participation. The amount of the compensation is chosen in order to be reasonable in relation to the type of task participants are involved. In the present questionnaire study, compensation equal to a cinema ticket was deemed to be reasonable.

3.4. Recommended TIS design

Based on the questionnaire study performed and the analysis performed using the Theory of Affordances, the selected TIS system has been identified (see Figure 16). The TIS is recommended to include the use of two panels which present text in one rectangular panel and a pictorial symbol in the other rectangular panel. Amber is the colour recommended for the written text in the panels. Flashing lights are particularly effective on increasing the attractiveness of the TIS and the subsequent attention of the test participants and they are recommended in the panel with the warning message. An increased size of the panels available in the TIS has a positive effect on capturing participants' attention. The amount of information contained in a single sign should be kept as small as possible in order to reduce people viewing time and the feeling of pressure. In addition, information should be appropriately separated. Written messages should be presented in double lines. The combined use of one pictorial symbol in one panel and text in the other panel resulted as particularly effective. The use of the emergency exit pictorial symbol in green resulted as the most effective pictorial symbol if compared with other symbols.

Figure 16. Recommended TIS design.

4. Emergency exit portals: colour scheme

The design of emergency exit portals should be made in order to increase the likelihood of motorists noticing and using the exits. To achieve this goal, different types of affordances should be taken into consideration. As described in the previous section about TIS, colour coding is an efficient tool to enhance cognitive affordance, i.e., it may improve the recognition and understanding of an object given the colour employed (Wickens, 2004). In particular, an efficient colour coding design can improve sensory affordance, since it can be used to increase the visibility of the emergency exit doors.

Colour coding should always be designed in order to match the type of information provided (Pastoor, 1990) in order to increase cognitive affordance. Emergency exit doors are generally painted in green since this colour is associated with safety in the context of transportation (Lai, 2010). In order to increase sensory affordance, it is also important to consider the contrast between the emergency exit portal and the colours of the tunnel walls.

4.1. Selected colour schemes of the portal

In line with the analysis presented in this section, different colour schemes are initially selected for the design of the emergency exit portal. In the Stockholm Bypass project, emergency exit portals are painted in the typical "safety green" since this colour is associated with safety in transportation and it increases cognitive affordance. The door design in the Stockholm Bypass project includes a circular window and a light is lit in the compartment behind the door. This is deemed to improve people's door recognition. Suggested emergency exit door colours are the "safety green", a "green darker than the safety green", white or grey. Schematic representations of the colour combinations are presented in Figure 17. The background colour of the environment is assumed to be grey in line with the standard colour of concrete.

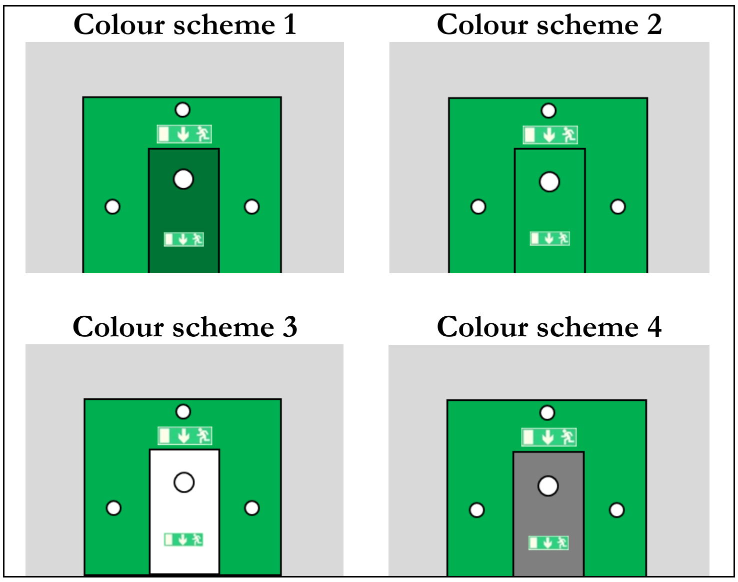


Figure 17. Schematic representation of four possible colour schemes for the emergency exit portals.

4.2. System evaluation

An evaluation of the performance of the suggested designs is made using the Theory of Affordances. Colour scheme is the only variable under consideration, thus the analysis is made in terms of sensory, cognitive and functional affordances. In fact, physical affordance is assumed to be equal in all portal designs since there are not changes in the physical elements of the door such as exit hardware.

4.2.1. Sensory affordance

Appropriate contrast of colours should be provided in order to increase sensory affordance (i.e. the emergency exit portal and door are visible and noticed). This is reflected in the fact that the emergency exit doors inside the portal should be easy to notice and distinguish in comparison with the other two colour schemes. This issue appears when using the same colour for the portal and the emergency exit door (e.g. Colour scheme 2) or using a door which has the same colour of the light coming from the window (e.g. Colour scheme 3). Possible factors affecting sensory affordance for each design are presented in Table 8. In this case, since the number of variables under consideration is small (i.e., colour contrast and colour of the door), the factors are listed without referring to a benchmark design (in contrast with the design of TIS where many variables may affect their design and a benchmark design has been used).

Table 8. Possible factors which may contribute to increase or decrease sensory affordance ("+" indicates a factor which increases affordance, while "-" indicates a factor which decreases it).

Colour scheme	Sensory affordance
1	+ Colour contrast between door and portal makes the door easy to be noticed/discovered + Colour contrast between door and portal makes the door easy to be distinguished
2	- Lack of colour contrast between door and portal makes the door hard to be noticed/discovered - Lack of colour contrast between door and portal makes the door hard to be distinguished
3	+ Colour contrast between door and portal makes the door easy to be noticed/discovered + Colour contrast between door and portal makes the door easy to be distinguished - Lack of colour contrast between the window of the door and the door makes the door hard to be distinguished
4	+ Colour contrast between door and portal makes the door easy to be noticed/discovered + Colour contrast between door and portal makes the door easy to be distinguished

4.2.2. Cognitive affordance

Green colour is generally associated with safety, thus the use of this colour for the door may generate a higher cognitive affordance than the white and grey colour for the door. The summary of the factors affecting the cognitive affordance of the designs is presented in Table 9.

Table 9. Possible factors which may contribute to increase or decrease cognitive affordance ("+" indicates a factor which increases affordance, while "-" indicates a factor which decreases it).

Colour scheme	Cognitive affordance
1	+ Green is associated with safety and it encourages emergency exit usage
2	+ Green is associated with safety and it encourages emergency exit usage
3	- White colour is not associated with safety and it does not encourage emergency exit usage - A possibly dirty door is not perceived as a safe place and it discourages emergency exit usage
4	- Grey colour is not associated with safety and it does not encourage emergency exit usage

4.2.3. Physical affordance

Physical affordance is not taken into account since it is assumed to be equal in all portal designs, i.e., no changes in the physical elements of the door are considered.

4.2.4. Functional affordance

Functional affordance is associated with the goals of the tunnel occupants. Main goals of the tunnel occupants include reaching a safe place overcoming possible property attachment (i.e. the reluctance to leave the vehicle) and social influence. The system designs under consideration are designed in line with these goals. For this reason, it is argued that functional affordance can be directly derived as a consequence of the factors affecting the other affordances (sensory and cognitive in this case). Those factors can be read in previous Table 8 and Table 9. Also in this case, the combination of high scores in the other affordances generates high functional affordance. If a system fails in terms of one of the affordances, the functional affordance will also be low as a result of the failing of that affordance.

Based on the factors analysed in Table 8 and Table 9, a qualitative ranking of the performance of the selected designs is presented in Table 10 using the Theory of Affordances to interpret them.

Table 10. Qualitative ranking of the colour schemes of the emergency exit portal and exit using the Theory of Affordances.

Colour scheme	Sensory affordance	Cognitive affordance	Physical affordance	Functional affordance
1	High	High	Not applicable	High
2	Low	High	Not applicable	Low/medium
3	Medium	Low	Not applicable	Low/medium
4	High	Low	Not applicable	Medium

4.3. Recommended portal colour scheme

Given the qualitative analysis made using the Theory of Affordances, the recommended colour scheme is colour scheme 1, i.e. safety green for the portal and a "green darker than the safety green" for the door (see Figure 18). Colour scheme 4 (grey door on a safety green portal) may be an alternative acceptable design.

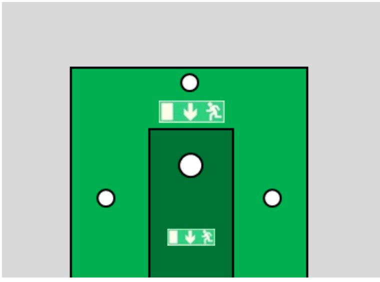


Figure 18. Recommended colour scheme of the portal.

5. Acoustic systems

Acoustic guidance can be a useful system to improve self-evacuation in road tunnel emergencies. This has been demonstrated in different experimental studies (Boer and Veldhuijzen van Zanten, 2007; Fridolf et al., 2013; Mellert and Welte, 2012; Nilsson et al., 2009). Acoustic systems may also useful to direct evacuees during their path if appropriate instructions are provided in the global message. In line with the Bypass Stockholm project design, this study investigates the use of global messages only, i.e. sound beacons are not taken into consideration. Therefore, the use of an acoustic system is mostly used to overcome the reluctance of evacuees to leave their vehicles and escape into the unknown.

Acoustic systems can divided into two main groups, namely 1) acoustic (warning) signals and 2) vocal messages.

The use of warning signals can have several positive effects on motorists (Nilsson et al., 2009) such as guiding people through smoke (Fridolf et al., 2013; Mellert and Welte, 2012). Warning signals may also enhance evacuees' walking speeds and they can be effective also in the case of good visibility (Boer and van Wijngaarden, 2004). Although the presence of a vocal message can produce a stronger compliance behaviour (Boer and Veldhuijzen van Zanten, 2007; Wogalter et al., 1993), it may results as quite difficult to perceive in a road tunnel given the issues associated with the general acoustic conditions (Nilsson et al., 2009). For this reason, the use of a warning signal as the only acoustic system is suggested.

The perceived urgency is one of the main factors which affect the effectiveness of an acoustic signal (Proulx, 2003). This is associated with different characteristics of the signal such as frequency, frequency patterns (the changes of frequency over time), pulse rate (the number of sound pulses per time) and sound level (Palmgren and Åberg, 2010) (see Figure 19).

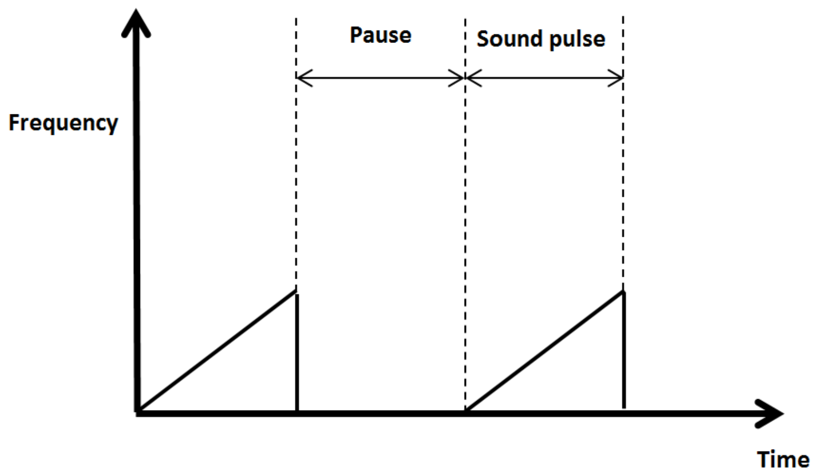


Figure 19. Schematic representation of a hypothetical signal, frequency vs time.

Recommended characteristics of warning signals include sufficient power and a wide frequency spectrum. This is made in order to overcome masking noise. It is also recommended to have rapid rise of pitch, and relatively rapid cycling time (Patterson, 1990; Stanton and Edworthy, 1999).

Frequency should be based on the peak sensitivity of human hearing (Fidell et al., 1974). Signals in the range of 0.7-4 kHz perform the best in capturing human attention (Oyer and Hardick, 1963). Recommended frequency range is between 0.8-1 kHz (Palmgren and Åberg, 2010). The use of multiple frequencies is often perceived as more urgent frequency pattern than a single-frequency signal (Oyer and Hardick, 1963). Pulse rate should be at least 1 Hz (Palmgren and Åberg, 2010). This is associated with the fact that signals with a longer silent period are generally perceived as less urgent (Haas and Edworthy, 1996; Stanton and Edworthy, 1999).

The sound level of an audible system can be significantly attenuated by the acoustical characteristics of the environment (Robinson, 1988). Factors affecting the audibility of signals include absorption, sound reflection, reverberation and diffraction. Those factors are dependent on the acoustic characteristics of the signal device, the location and spacing of the devices, the sound transmission loss of the materials and the background noise level (Robinson, 1988). High sound levels (generally expressed in decibels [dB]) are perceived as more urgent than low sound levels (Edworthy, 2011). Nevertheless, too high sound levels may be perceived as annoying by the evacuees. Optimal sound levels are in the range of 80-100 dB (Edworthy, 2011).

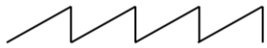
Reaction time to visual signals is generally improved when they are accompanied by an auditory warning system (Brewster, 1997; De Lorenzo and Eilers, 1991). It is also important to note that the use of too many cues for increasing the perception of hazard, e.g. a triple-flash mode at a high flash rate (Chan and Ng, 2009) can be annoying and might not improve hazard awareness. Designers are therefore recommended to use a combination of visual and acoustic systems, trying to achieve a balance between transmitted hazard awareness and information overload. In this context, it is relevant to test the combination of specific visual and acoustic systems. Nevertheless, this is not within the objectives of the present document.

5.1. Selected acoustic systems

Based on the review presented in this section, the use of a vocal message is not recommended since sensory and cognitive affordances may be reduced by the fact that the content of the message may be unclear due to the acoustic conditions of the tunnel. The suggested acoustic system consists instead of a warning signal.

Based on the review performed, the warning signal should be continuous; it should have a pulse rate of at least 1Hz and in a frequency range of 0.8-1 kHz. Possibly suitable signals have been found in either British Standards (BS, 2013) or Swedish Standard (Palmgren and Åberg, 2010) and they are presented in Table 11.

Table 11. Main characteristics of the selected warning signals.

Signal	Standard	Frequency pattern	Frequency range [Hz]	Visual image of the frequency pattern
BS	British standard (BS, 2013)	Alternating: 0.25 s high, 0-25 low	800-970	
F_SAW	British standard (BS, 2013)	Rising:0.14 s (7Hz)	800-970	
SIS_2	Swedish standard	Mechanical bell	-	-

5.2. System evaluation

The evaluation of the warning signals is made using the Theory of Affordances. It should be noted that acoustical systems are sensory systems, thus the study of physical affordance is not applicable for them.

5.2.1. Sensory affordance

Sensory affordance is associated with the frequency range, sound levels and patterns. Frequency range and sound levels are in the same range in the BS and F_SAW warning signals. A rising frequency pattern is deemed to increase the chances to be heard by the evacuees, while no discernible frequency changes (as in the case of SIS_2) are deemed to decrease sensory affordance. For this reason, sensory affordance is deemed to be higher in the F_SAW warning signal and lower in the SIS_2 signal. The factors affecting sensory affordance for each design are listed in Table 12.

Table 12. Possible factors which may contribute to increase or decrease sensory affordance ("+" indicates a factor which increases affordance, while "-" indicates a factor which decreases it).

Signal	Sensory affordance
1	+ Appropriate frequency range enhances signal audibility
2	+ Appropriate frequency range enhances signal audibility + Rising frequency pattern can be more easily heard by evacuees
3	+ Appropriate frequency range enhances signal audibility - No discernible frequency changes decrease the chances of the signal to be heard by evacuees

5.2.2. Cognitive affordance

Cognitive affordance is affected by the degree of perceived urgency. This is associated with the frequency pattern and the pulse rate. An alternate pattern generates a higher degree of perceived urgency, thus increasing the associated affordance. The F_SAW signal presents a high pulse rate (7 Hz) which is deemed to generate high cognitive affordance as well. On one hand, BS and F_SAW warning signal are deemed to have a better performance in terms of cognitive affordance than the SIS_2 signal, which does not present discernible frequency changes. On the other hand, SIS_2 is the most common warning signal in Sweden, and familiarity with the signal may increase the understanding of the meaning of the signal in a Swedish population. The summary of the factors affecting the cognitive affordance of the designs is presented in Table 13.

Table 13. Possible factors which may contribute to increase or decrease cognitive affordance ("+" indicates a factor which increases affordance, while "-" indicates a factor which decreases it).

Signal	Cognitive affordance
1	+ Alternate pattern enhances perceived urgency
2	+ Alternate pattern enhances perceived urgency + High pulse rate enhances perceived urgency
3	- No discernible frequency changes decreases the degree of perceived urgency + Familiarity with the signal in Swedish population increases the understanding of the message

5.2.3. Physical affordance

The system under consideration is a sensory system, thus the analysis of physical affordance is not applicable in this case.

5.2.4. Functional affordance

Functional affordance is associated with the goals of the motorists. Main goals of the motorists include reaching a safe place overcoming possible property attachment (i.e. the reluctance to leave the vehicle) and social influence. The systems under consideration are designed in line with these goals. For this reason, it is argued that functional affordance can be directly derived as a consequence of the factors affecting the other affordances (sensory and cognitive in this case since acoustic signals are sensory systems). Those factors can be read in previous Table 12 and Table 13. The combination of high scores in the other affordances generates high functional affordance. If a system fails in terms of one of the affordances, the functional affordance will also be low as a result of the failing of that affordance.

The analysis of the factors affecting the affordances permits the assessment of global qualitative scores for each design (see Table 14).

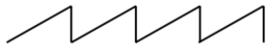
Table 14. Qualitative ranking of the colour schemes of the emergency exit portal and exit using the Theory of Affordances.

Signal	Sensory affordance	Cognitive affordance	Physical affordance	Functional affordance
BS	Medium	High	/	Medium/high
F_SAW	High	High	/	High
SIS_2	Medium	Medium	/	Medium

5.3. Recommended acoustic system

Vocal messages are not recommended since they may result as quite difficult to perceive in tunnels. The use of a warning signal is recommended. F_SAW signal (see Table 15) is the selected signal due to the comparison of the scores obtained in terms of affordances produced by the three possible signals. It is recommended to install the F_SAW signal in the tunnel with a sound level defined in accordance with the estimated background noise in the tunnel (e.g., in buildings optimal sound level is generally in a range of 80-100 dB). The suggested acoustic system will need to be tested/measured and calibrated in the tunnel with cars and inside the cars.

Table 15. Recommended Acoustic system

Signal	**Standard**	**Frequency pattern**	**Frequency range [Hz]**	**Visual image of the frequency pattern**
F_SAW	British standard (BS, 2013)	Rising:0.14 s (7Hz)	800-970	

6. Future research

The present work presents a list of recommendations on TIS design, colour scheme of the emergency exit portals and acoustic systems for road tunnel evacuation based on a literature review and the analysis of different design variables conducted using the Theory of Affordances. In particular, an affordance-based questionnaire has been used to investigate different variables affecting TIS designs, while a qualitative evaluation based on the Theory of Affordances has been performed for the assessment of different design solutions for the colour scheme of the emergency exit portals and acoustic systems for road tunnel evacuation.

It is important to note that this work should be considered as a preliminary study on the characteristics of different systems to be adopted for improving the safety of road tunnels in case of evacuation. In fact, in order to increase the validity of the assessment of the design features selected in the present work, future research should test those features in a real tunnel environment. This means that the present work should be interpreted as a first step towards the assessment of the optimal features of different safety design systems for road tunnel evacuation rather than a final solution to the problem. In fact, full scale testing in the real world would permit confirming and validating the findings of the present study as well as allowing a further analysis of the behaviours of evacuees in case of a road tunnel emergency. To address this issue, a real world testing of the design solution discussed in the present work will be performed in a full scale tunnel evacuation experiment at the Norra Länken tunnel in Stockholm.

References

Åberg, A., Clevström, J., Luthander, P., 2008. Lastbil brann i Södra länken.

AFS, 2008. AFS 2008:13 Skyltar och signaler - Arbetsmiljöverket.

American National Standards Institute, 2011. ANSI Z535.

Boer, L.C., van Wijngaarden, S.J., 2004. Directional sound evacuation from smoke-filled tunnels. Presented at the Safe & Reliable Tunnels. Innovative European Achievements, Prague, Czech Republic.

Boer, L.C., Veldhuijzen van Zanten, D.W., 2007. Behaviour on tunnel fire, in: Waldau, N., Gattermann, P., Knoflacher, H., Schreckenberg, M. (Eds.), Pedestrian and Evacuation Dynamics 2005. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 91–98.

Borowsky, A., Shinar, D., Parmet, Y., 2008. Sign location, sign recognition, and driver expectancies. Transp. Res. Part F Traffic Psychol. Behav. 11, 459–465. doi:10.1016/j.trf.2008.06.003

Boschker, M.S.J., Bakker, F.C., Michaels, C.F., 2002. Memory for the Functional Characteristics of Climbing Walls: Perceiving Affordances. J. Mot. Behav. 34, 25–36. doi:10.1080/00222890209601928

Brewster, S.A., 1997. Using non-speech sound to overcome information overload. Displays 17, 179–189. doi:10.1016/S0141-9382(96)01034-7

British Standards, 2013. BS 5839-1:2013 Fire detection and fire alarm systems for buildings.

Chan, A.H.S., Ng, A.W.Y., 2009. Perceptions of implied hazard for visual and auditory alerting signals. Saf. Sci. 47, 346–352. doi:10.1016/j.ssci.2008.06.003

Christ, R.E., 1975. Review and Analysis of Color Coding Research for Visual Displays. Hum. Factors J. Hum. Factors Ergon. Soc. 17, 542–570.

De Lorenzo, R.A., Eilers, M.A., 1991. Lights and siren: A review of emergency vehicle warning systems. Ann. Emerg. Med. 20, 1331–1335. doi:10.1016/S0196-0644(05)81076-5

Dudek, C.L., 1991. Guidelines on the use of changeable message signs.

Dudek, C., Ullman, G., 2001. Variable Message Sign Operations Manual.

Dudek, C., Ullman, G., 2002. Flashing Messages, Flashing Lines, and Alternating One Line on Changeable Message Signs. Transp. Res. Rec. 1803, 94–101. doi:10.3141/1803-13

Edworthy, J., 2011. Designing Effective Alarm Sounds. Biomed. Instrum. Technol. 45, 290–294. doi:10.2345/0899-8205-45.4.290

Endsley, M.R., 1995. Toward a Theory of Situation Awareness in Dynamic Systems. Hum. Factors J. Hum. Factors Ergon. Soc. 37, 32–64. doi:10.1518/001872095779049543

Fidell, S., Pearsons, K.S., Bennett, R., 1974. Prediction of Aural Detectability of Noise Signals. Hum. Factors J. Hum. Factors Ergon. Soc. 16, 373–383.

Fridolf, K., Ronchi, E., Nilsson, D., Frantzich, H., 2013. Movement speed and exit choice in smoke-filled rail tunnels. Fire Saf. J. 59, 8–21. doi:10.1016/j.firesaf.2013.03.007

Gibson, J.J., 1977. Perceiving, acting, and knowing: toward an ecological psychology. Lawrence Erlbaum Associates ; distributed by the Halsted Press Division, Wiley, Hillsdale, N.J. : New York.

Haas, E.C., Edworthy, J., 1996. Designing urgency into auditory warnings using pitch, speed and loudness. Comput. Control Eng. J. 7, 193–198. doi:10.1049/cce:19960407

Hartson, H.R., 2003. Cognitive, physical, sensory, and functional affordances in interaction design. Behav. Inf. Technol. 22, 315–338.

International Standards Organization, 2011. ISO 3864-1:2011 Graphical symbols - Safety colours and safety signs.

Joo, J., Kim, N., Wysk, R.A., Rothrock, L., Son, Y.-J., Oh, Y., Lee, S., 2013. Agent-based simulation of affordance-based human behaviors in emergency evacuation. Simul. Model. Pract. Theory 32, 99–115. doi:10.1016/j.simpat.2012.12.007

Kim, N., Joo, J., Rothrock, L., Wysk, R., Son, Y.-J., 2011. Human Behavioral Simulation Using Affordance-Based Agent Model, in: Jacko, J.A. (Ed.), Human-Computer Interaction. Design and Development Approaches. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 368–377.

Koyuncu, M., Amado, S., 2008. Effects of stimulus type, duration and location on priming of road signs: Implications for driving. Transp. Res. Part F Traffic Psychol. Behav. 11, 108–125. doi:10.1016/j.trf.2007.08.005

Lai, C.J., 2008. An Ergonomic Study Of Chinese Font And Color Display On Variable Message Signs. J. Chin. Inst. Ind. Eng. 25, 306–313. doi:10.1080/10170660809509094

Lai, C.J., 2010. Effects of color scheme and message lines of variable message signs on driver performance. Accid. Anal. Prev. 42, 1003–1008. doi:10.1016/j.aap.2009.12.002

Lai, C.J., 2012. Drivers' comprehension of traffic information on graphical route information panels. Accid. Anal. Prev. 45, 565–571. doi:10.1016/j.aap.2011.09.008

Liu, Y.-C., 2005. A simulated study on the effects of information volume on traffic signs, viewing strategies and sign familiarity upon driver's visual search performance. Int. J. Ind. Ergon. 35, 1147–1158. doi:10.1016/j.ergon.2005.06.009

Mellert, L.D., Welte, U., 2012. Acoustical Guidance in Road Tunnels. Presented at the 6th International Conference Tunnel Safety and Ventilation, Graz, pp. 187–194.

Nilsson, D., 2009. Exit choice in fire emergencies: influencing choice of exit with flashing lights. Dept. of Fire Safety Engineering and Systems Safety, Lund University, Lund, Sweden.

Nilsson, D., Johansson, A., 2009. Social influence during the initial phase of a fire evacuation—Analysis of evacuation experiments in a cinema theatre. Fire Saf. J. 44, 71–79. doi:10.1016/j.firesaf.2008.03.008

Nilsson, D., Johansson, M., Frantzich, H., 2009. Evacuation experiment in a road tunnel: A study of human behaviour and technical installations. Fire Saf. J. 44, 458–468. doi:10.1016/j.firesaf.2008.09.009

Ou, Y.-K., Liu, Y.-C., 2012. Effects of sign design features and training on comprehension of traffic signs in Taiwanese and Vietnamese user groups. Int. J. Ind. Ergon. 42, 1–7. doi:10.1016/j.ergon.2011.08.009

Oyer, H.J., Hardick, E.J., 1963. Response of population to optimum warning signal, Defense Technical Information Center. Michigan State university. Department of speech.

Palmgren, R., Åberg, J., 2010. Vilka ljud - och ljussignaler passar bäst som utrymningslarm? En undersökning av egenskaper hos signaler (No. 5345). Department of Fire Safety Engineering and Systems Safety, Lund University.

Pastoor, S., 1990. Legibility and Subjective Preference for Color Combinations in Text. Hum. Factors J. Hum. Factors Ergon. Soc. 32, 157–171. doi:10.1177/001872089003200204

Patterson, R.D., 1990. Auditory warning sounds in the work environment. Philos. Trans. R. Soc. B 327, 485–492.

Proulx, G., 2003. Recollection, Identification and Perceived Urgency of the Temporal-Three Evacuation Signal. J. Fire Prot. Eng. 13, 67–82. doi:10.1177/1042391503013001004

Robinson, D.A., 1988. Sound attenuation in buildings: Implications for fire alarm system design. Fire Saf. J. 14, 5–12. doi:10.1016/0379-7112(88)90040-9

Sanders, M.S., 1993. Human factors in engineering and design, 7th ed. ed. McGraw-Hill, New York.

Shields, T.J., 2005. Human behaviour in tunnel fires, in: The Handbook of Tunnel Fire Safety. Thomas Telford Ltd., London, pp. 323–342.

Shinar, D., Vogelzang, M., 2013. Comprehension of traffic signs with symbolic versus text displays. Transp. Res. Part F Traffic Psychol. Behav. 18, 72–82. doi:10.1016/j.trf.2012.12.012

Sixsmith, A., Sixsmith, J., Canter, D.V., 1988. When is a door not a door? A study of evacuation route identification in a large shopping mall. Safety in the built environment. E. & F.N. Spon, London ; New York.

Stanton, N., Edworthy, J., 1999. Human factors in auditory warnings. Ashgate, Aldershot; Brookfield, VT.

Thackray, R.I., Mark Touchstone, R., 1991. Effects of monitoring under high and low taskload on detection of flashing and coloured radar targets. Ergonomics 34, 1065–1081. doi:10.1080/00140139108964847

Wang, J.H., Cao, Y., 2003. A Human Factors Study on Message Design of Variable Message Signs. Int. J. Ind. Eng. 10, 339–344.

Wang, J.H., Collyer, C.E., Yang, C.M., 2006. Enhancing motorist understanding of variable message signs.

Wickens, C.D., 2004. An introduction to human factors engineering, 2nd ed. ed. Pearson Prentice Hall, Upper Saddle River, N.J.

Wickens, C.D., 2013. Engineering psychology and human performance, Fourth edition. ed. Pearson, Boston.

Wogalter, M.S., Kalsher, M.J., Racicot, B.M., 1993. Behavioral compliance with warnings: effects of voice, context, and location. Saf. Sci. 16, 637–654. doi:10.1016/0925-7535(93)90028-C

Wolff, J.S., Wogalter, M.S., 1998. Comprehension of Pictorial Symbols: Effects of Context and Test Method. Hum. Factors J. Hum. Factors Ergon. Soc. 40, 173–186. doi:10.1518/001872098779480433

Wright, J.M.V., 1968. Selection in visual immediate memory. Q. J. Exp. Psychol. 20, 62–68. doi:10.1080/14640746808400128

Appendix 1. Example of recruitment letter

LUNDS TEKNISKA HÖGSKOLA
Lunds universitet

Brandteknik och riskhantering
Daniel Nilsson

Rekryteringsinformation

Enkätstudie om utformningen av trafikinformationsskyltar (TIS)

Den 27 november genomför avdelningen Brandteknik och riskhantering, LTH, en enkätstudie. I studien kommer olika utformningar av trafikinformationsskyltar (TIS) i tunnlar att utvärderas. Du kommer att titta på möjliga utformningar av TIS medan du fyller i en enkät.

Studien tar totalt 30 minuter och genomförs i sal A:B i A-huset, LTH. Medverkan är frivillig och du får en biocheck (biocheck på SF bio) om du deltar. Antalet platser är begränsat till 20 personer. Du har fått denna information eftersom du är en av de 20 personer som anmält sig till studien.

Enkätstudien kommer att genomföras följande tid:

27/11 (onsdag) kl. 12.15-12.45 i sal A:B i A-huset, LTH

Om du har några frågor om studien kan du kontakta Daniel Nilsson via mejl (daniel.nilsson@brand.lth.se) eller telefon (046-222 95 93).

Hälsningar

Daniel Nilsson

Daniel Nilsson

Postadress Box 118, 22100 Lund *Besöksadress* John Ericssons väg 1, Lund
Telefon dir 046-222 95 93,
växel 046-222 73 60 *telefax* 046-222 46 12 *E-post* daniel.nilsson@brand.lth.se
Internet http://www.brand.lth.se

Appendix 2. Affordance-based TIS Questionnaire

THE QUESTIONNAIRE:

As part of a research study on traffic information signs in tunnels, you will be asked to fill out a questionnaire. There are 10 questions relating to demographics, and 5 questions relating to the traffic information sign designs repeated for four pair of signs. The entire process will be completed in approximately 20-25 minutes.

YOUR ANSWERS:

Your information will be treated confidentially and it will not be possible to trace your replies back to you in the presentation of the results. Data will be stored for research purposes and may be published and shown in public.

RIGHT TO WITHDRAW:

You have the right at any time to withdraw from the questionnaire by telling this to your interviewer.

TRAFFIC INFORMATION SIGN QUESTIONNAIRE:

The questionnaire contains questions about a hypothetical scenario in a road tunnels:

> "Imagine the following scenario: You are driving your car in a tunnel when the traffic suddenly stops. The signs on the roof are turned on and an alarm sounds in the tunnel *[Föreställ dig följande scenario: Du kör din bil i en tunnel när trafiken plötsligt stannar. Skyltar i taket sätts på och det hörs ett larm i tunneln.]*
>
> On the screens in front of you, you will see two possible configurations of the signs in the roof of the tunnel, i.e., A and B. Look at the two configurations while you fill out page 1 of the questionnaire. Try to imagine the scenario in the tunnel when you answer the questions *[På skärmarna framför dig ser du två möjliga utformningar av skyltarna i taket på tunneln, dvs A och B. Titta på de två utformningarna medan du fyller i sida 1 i enkäten. Försök att tänka dig in i scenariot i tunneln när du besvarar frågorna.]*"
>
> Repeat message (new designs):
>
> On the screens in front of you, you will see two possible designs of the signs in the roof of the tunnel, ie, A and B. Look at the two configurations while filling in page X in the questionnaire. Try to imagine the scenario in the tunnel when you answer the questions. *[På skärmarna framför dig ser du två möjliga utformningar av skyltarna i taket på tunneln, dvs A och B. Titta på de två utformningarna medan du fyller i sida X i enkäten. Försök att tänka dig in i scenariot i tunneln när du besvarar frågorna.]*"
>
> X = 2, 3 or 4

TEST X (X= 1, 2, 3, 4, or 5)

1. Vilken av de två utformningarna är lättast att upptäcka?

A ☐ B ☐ A och B är likvärdiga ☐

Förklara varför just denna utformning är lättast att upptäcka:

____

____

2. I vilken av de två utformningarna är det lättast att urskilja detaljerna?

A ☐ B ☐ A och B är likvärdiga ☐

Förklara varför det är lättast att urskilja detaljerna i just denna utformning:

____

____

3. Vilken av de två utformningarna förmedlar bäst budskapet att du ska lämna din bil?

A ☐ B ☐ A och B är likvärdiga ☐

Förklara varför just denna utformning bäst förmedlar budskapet att du ska lämna din bil:

____

____

4. Vilken av de två utformningarna förmedlar bäst budskapet att du ska använda en nödutgång?

A ☐ B ☐ A och B är likvärdiga ☐

Förklara varför just denna utformning bäst förmedlar budskapet att du ska använda en nödutgång:

____

____

5. Vilken av de två utformningarna erbjuder totalt sett bäst stöd för din utrymning.

A ☐ B ☐

BAKGRUNDSFRÅGOR

1. Ålder: ____

2. Nationalitet: ____

3. Kön:

Man ☐ Kvinna ☐

4. Vilka av följande språk kan du läsa och förstå? (du kan välja mer än ett alternativ)

Svenska ☐ Engelska ☐

5. I vilket land är du bosatt?

Sverige ☐ Annat, ange:

____

6. Är du färgblind?

Ja ☐ Nej ☐

Om Ja, ange vilken typ av färgblindhet:

____

7. Vad är din huvudsakliga sysselsättning?

____

8. Har du körkort?

Ja ☐ Nej ☐

9. Hur ofta kör du i vägtunnlar? (välj det alternativ som passar bäst)

mer sällan än en gång per år ☐

en gång per år ☐

en gång per månad ☐

en gång per vecka ☐

varje dag ☐

10. Har du tidigare erfarenhet av någon nödsituation i en vägtunnel?

Ja ☐ Nej ☐

Om Ja, förklara:

____