

NATIONAL
COOPERATIVE
HIGHWAY
RESEARCH
PROGRAM

NCHRP

Web-Only Document 216:

Emergency Exit Signs and Marking Systems for Highway Tunnels

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Contractor's Final Report for NCHRP Project 20-59(47)
Submitted August 2015



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ACKNOWLEDGMENT

This work was sponsored by the American Association of State Highway and Transportation Officials (AASHTO), in cooperation with the Federal Highway Administration, and was conducted in the National Cooperative Highway Research Program (NCHRP), which is administered by the Transportation Research Board (TRB) of the National Academies of Sciences, Engineering, and Medicine.

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ACKNOWLEDGMENTS

The research reported herein was performed under NCHRP Project 20-59(47) by the Texas A&M Transportation Institute (TTI), a member of The Texas A&M University System. The research team gratefully acknowledges the input of the Regulatory and Warning Signs Technical Committee of the National Committee on Uniform Traffic Control Devices, as well as that provided by the 20-59(47) project panel. Thanks also go to Jeremy Johnson, Dan Walker, Ivan Lorenz, Kai Johnson, Sarah Hammond, Christine Yager, Sarah Badillo, Paige Ericson, David Dobrovolsky, Neal Johnson, and Rod Cavness, all of TTI, for their valuable help with preparing for and conducting data collection for the human factors studies, and to Dr. Srinivas Geedipally of TTI for his input on data analysis.

ABSTRACT

This research project focused on determining effective messages for encouraging drivers to leave their vehicles and evacuate a tunnel on foot; determining sign and marking formats that most effectively lead people to emergency tunnel exits; and determining the most visible sign and marking materials and technologies for use in highway tunnel environments.

Focus groups were conducted to explore potential evacuation messages and delivery methods. Next, a simulated tunnel environment was used to test driver responses to emergency messages, and to test visibility and comprehension of selected emergency exit signs and markings, including the running man pictogram prescribed in the International Organization for Standardization's 7010 guidelines. Results indicate that the running man pictogram was correctly or partially understood as indicating an exit by a majority of participants, and that a directional sign with the pictogram, "EXIT" text, a directional arrow, and distance in feet was correctly understood by virtually all participants. Visibility distances of tested internally illuminated signs were somewhat longer than those of tested photoluminescent signs; visibility for all sign technologies dropped sharply when viewed through smoke. The final product is a proposed set of guidelines for emergency exit signs, markings, and messages for use in tunnels in the United States, published as a brochure, which can be found at <http://www.trb.org/Main/Blurbs/173414.aspx>.

EXECUTIVE SUMMARY

Emergencies such as vehicle crashes, fires, hazardous waste spills, or terrorist activities can be particularly hazardous when they occur inside long underground tunnels. The enclosed environment of a highway tunnel can concentrate heat, smoke, or other toxic gases resulting from the incident; limited right-of-way means that even a partially blocked lane can potentially trap vehicles and hinder access for emergency responders. As a result, tunnel users may need to evacuate themselves on foot via emergency exits. This research study examined emergency exit signs, markings, and messages intended for use in highway tunnels. The study's three primary objectives were as follows:

- To evaluate the effectiveness of emergency messages and their delivery methods (i.e., visual, audible, or both) to encourage drivers to leave their vehicles and evacuate a tunnel on foot.
- To evaluate the effectiveness of sign messages, as well as signing and marking formats, to lead people to emergency tunnel exits.
- To evaluate the visibility of different sign and marking materials and technologies for use in highway tunnel environments, in particular when a tunnel is filled with smoke.

BACKGROUND

Studies of past tunnel emergencies have found that tunnel users often do not act independently to evacuate themselves on foot, instead choosing to remain in or near their vehicles. Some reasons for making the potentially fatal decision not to evacuate are the lack of awareness of an unfolding hazard, uncertainty about the appropriate course of action, reluctance to leave the perceived safety of the vehicle, and reluctance to abandon property. During an emergency, people have a tendency to wait for information or instruction rather than seeking it out. If and when people do decide to exit a tunnel in the face of a recognized danger, a common tendency is to try to reach the main tunnel portal entrance through which they drove into the tunnel, rather than emergency exits for pedestrians, which may be nearer. In fact, drivers may not be aware of the existence of emergency exits or cross passageways and therefore may not recognize the purpose of exit doors along the tunnel wall. Additionally, people tend to overestimate the amount of time they have to evacuate during a fire, a potentially fatal mistake since fire and smoke can spread more quickly in a tunnel fire than in a building.

In the absence of emergency responders to give directions, in-tunnel signs, marking systems, lighting, and/or audible signals must provide direction to tunnel users. Both the need to evacuate and the location of the nearest emergency exits must be clearly communicated. Additionally, the signs and markings must be visible to pedestrians under potentially adverse viewing conditions, including darkness and smoke. Existing guidelines that address aspects of emergency exit signs and markings for highway tunnels include the following:

- Directive 2004/54/EG of the European Parliament establishes minimum safety requirements for all roadway tunnels on the Trans European Roadway Network that are longer than 500 meters. One of the objectives of the guidelines is to improve conditions for self-rescue from a tunnel in an emergency, including guidelines for evacuation lighting and signing.

- The National Fire Protection Association (NFPA) is a nonprofit organization with members from nearly 100 nations. As part of its mission, NFPA has developed approximately 300 codes and standards for mitigating the risk and effects of fires. Three NFPA codes that directly address emergency exit signs and markings for highway tunnels are NFPA 502, *Standard for Road Tunnels, Bridges, and Other Limited Access Highways*; NFPA 170, *Standard for Fire Safety and Emergency Symbols*; and NFPA 101, *Life Safety Code*.
- The International Building Code's (IBC's) guidelines do not directly apply to exit door and exit pathway signs and markings in tunnels; however, they represent a standard for exit signing in buildings that is consistent and recognized throughout the United States.
- The International Commission on Illumination's (CIE's) 193-2010 Emergency Lighting in Road Tunnels provides guidelines for emergency lights and markings for pedestrians in highway tunnels, including marking recommendations for emergency exit doors.

RESEARCH APPROACH AND RESULTS

Building on prior research and existing U.S., European, and international standards for emergency exit signs and markings, researchers tested selected messages, sign and marking formats, and sign and marking technologies with volunteer participants. Research activities included focus group discussions and a simulation of a tunnel emergency situation involving smoke. The expert panel discussion included tunnel operators and emergency responders, and their responses were used to revise the focus group discussion and tunnel fire simulation, as well as to identify potential maintenance or other technical issues associated with signs and markings.

Focus Group Discussions

Two focus group discussions were conducted to gain a better understanding of how tunnel users might respond to various tunnel incident scenarios and warnings. Participants were presented with pictures, videos, and audio clips pertaining to a hypothetical emergency involving fire inside a highway tunnel. Participants discussed how they might react to a similar situation, what types of information and messages would be most effective, and what might influence their decisions to either stay in their vehicle or evacuate the tunnel on foot. The results of the focus group discussions included the following:

- Participants indicated that uncertainty about what is happening might lead to a delayed or incorrect response, so it would be important to relay to tunnel occupants details about the emergency or at least instruct the drivers to evacuate the tunnel.
- The messages that participants found most useful included a brief statement about the emergency, followed by a direct action statement. Examples of this type of message, displayed on an electronic message sign, included "Emergency—walk to exits" and "Fire in tunnel—walk to exits." Audio messages including the same information elements were also considered effective.

Tunnel Simulation

The tunnel simulation tested individual responses to a tunnel emergency scenario similar to those discussed by the focus groups and tested several sign and marking formats and

technologies within the simulated tunnel environment, both for participants' comprehension of and confidence in various formats and for detection and legibility distances through smoke.

Response to Emergency Situation and Messages

Stage 1 of the tunnel exercise simulated a vehicle trip through a highway tunnel that was stopped by a traffic jam, followed by the appearance of smoke in the tunnel and sounds of stopped traffic and tunnel ventilation. One-third of participants received only these visual and auditory cues to the situation, another one-third also saw a dynamic message sign (DMS) with the message "Fire in tunnel—walk to exits," and a final one-third heard a longer audio message: "Attention—there is a vehicle fire in the tunnel. Turn off your engine and leave your keys in the vehicle so that it can be moved by emergency personnel. Leave your vehicle and walk quickly to emergency exits." Results of Stage 1 included the following:

- While all three groups included participants who indicated that they would stay in their vehicle as well as participants who indicated they would leave the vehicle, the two groups of participants who received a message about the incident (either visually or audibly) were much more likely to say they would leave the vehicle and exit on foot (81 percent of those who saw the DMS and 73 percent of those who heard the audio announcement) versus the group who received no message (20 percent).
- When asked what additional information they would want or need regarding the situation, participants who had not received a message were most likely to request information about the nature and seriousness of the situation, as well as instructions about what they should do. Participants who had received either of the two messages were most likely to ask about the locations of the exits and how to identify them.

Sign Comprehension

Participants viewed nine signs. Three of the signs were symbol-only signs: a "running man" symbol-only sign, a "refuge point" sign, and an emergency telephone sign. Researchers asked participants what they thought each of these signs meant. The other six signs all incorporated the word "EXIT," and participants were asked where they would expect to find an exit door based on each sign. Some of the principal results from the comprehension testing included the following:

- The stand-alone running man symbol was identified correctly by 48 percent of participants as an exit sign, while another 38 percent assumed that the sign indicated a direction or path for them to follow.
- All signs that included the word "EXIT" were correctly identified by all participants as indicating a tunnel exit. Comprehension scores for signs with "EXIT" text, therefore, measured participants' understanding of an exit's location relative to the location of the sign.
- Once the running man symbol was paired with the word "EXIT," most participants thought that the running man sign (with or without the word "EXIT") indicated a direction, even without a supplemental arrow. Therefore, participants most frequently assumed that the running man symbol indicated an exit to the side of the sign or farther away in the direction that the running figure was facing. However, participants saw the

test signs in the context of a wall-mounted frame and so did not have the added context of a visible doorway.

- A small number of participants did not recognize the chevron arrows on a text-only EXIT sign as directional arrows. All participants recognized tailed arrows as indicating a direction.
- When the running man sign was paired with a (tailed) directional arrow and a distance, comprehension of the exit's location relative to the sign was perfect among nearly all participants.
- When a running man exit sign included an arrow but no specified distance, many participants assumed that an exit was nearby in the direction of the arrow; if no distance was provided, they assumed the distance to the exit was very short.

Path Marking Preferences

Participants were presented with four pairs of exit path/door marking formats and asked to select the option from each pair that they would feel most confident about following to an exit:

- Steady-state light-emitting diode (LED) lights vs. LED lights flashing in unison.
- Unison-flash LED lights alone vs. unison-flash LED lights plus an audio beacon saying, "Exit here."
- Unison-flash LED lights vs. traveling LED lights that illuminated in a left-to-right sequence.
- Unison-flash LED lights plus an "exit here" audio beacon vs. traveling LED lights.

In general, participants preferred flashing lights over steady-state lights, and traveling lights that indicated a direction over unison-flash lights. An audio beacon was a favored option to indicate the location of doorway; however, when the audio beacon was compared against traveling/directional pathway lights, many participants indicated that the traveling lights would be more useful farther away from an exit door, and the audio beacon would be helpful close to the door.

Sign Visibility

To assess the visibility of the signs tested, researchers measured the luminance of each sign's positive (brighter) and negative (darker) areas, as well as of the gray walls and frames surrounding the signs. Measurements were conducted in clear conditions and in smoky conditions with smoke opacity levels of 4, 5, 10, 12 and 23 percent, and in both low ambient light and darkness. The measurements were used to calculate the contrast ratio of each sign compared to the tunnel wall, and also the contrast ratio of each sign's positive and negative elements, i.e., sign legend versus sign background. Sign visibility was also measured during participant testing in the tunnel simulation by recording the distances at which participants could detect and read each sign. Some of the signs were internally illuminated by LEDs, while others were photoluminescent (PL).

Luminance and Contrast in Smoke

The luminance measurements showed that the overall luminance levels and the contrast ratios between signs and the tunnel wall, and between the sign legends and background, all

diminished sharply when the signs were viewed through smoke. This significantly affected how far away signs could be seen and also reduced the contrast between their light and dark areas, which made text and symbols more difficult to read. The principal findings from the luminance measurements included the following:

- In general, LED signs in clear conditions had much higher luminance levels than PL signs, and this difference continued when signs were measured in smoky conditions. However, these differences in luminance diminished as smoke opacity increased.
- Under low levels of ambient light, the contrast of sign luminance with the tunnel wall diminished rapidly as smoke opacity increased. In general, LED signs slightly outperformed PL signs. When there was no ambient light, contrast between the tested signs and the tunnel walls was much higher, and PL signs displayed higher contrast ratios than LED signs.
- Contrast ratios between sign legends and backgrounds were consistently higher for PL signs than for LED signs. This was the case with low levels of ambient light and was even more pronounced without ambient light.

Detection and Legibility Distances

During the tunnel simulation, detection and legibility distances were recorded for each sign that participants viewed, as well as for a photoluminescent path marking square. Some of the findings from visibility testing of the signs with study participants included the following:

- For all of the signs, smoke density/opacity was a significant factor in detection and visibility distances, as would be expected from the sharp drop in sign/markings luminance and contrast that was seen in the photometric measurements.
- The LED signs that were tested could be seen from farther away than the tested PL signs, as would be expected from the LED signs' higher luminance values.

PROPOSED GUIDELINES

The findings from the study are summarized in a set of proposed guidelines for the format and placement of emergency exit signs and markings for highway tunnels. The guidelines also address considerations for selecting sign and marking materials and technologies, as well as some preliminary recommendations for public outreach and education pertaining to tunnel emergencies and exit plans. Highlights from the proposed guidelines include the following:

- **Emergency Exit Sign Formats.** Emergency exit door and directional signs should include the running man symbol in combination with the word "EXIT," as shown in Figure 1. Sign colors should be green and white. This sign should be placed on the exit door if possible, or on the tunnel wall immediately to the right or left of the door, preferably with the midpoint of the sign no higher than 1.5 meters (4.9 feet) above the floor.



Figure 1. Exit door sign format.

- **Emergency Exit Directional Sign Formats.** Signs indicating directions to emergency exits should be placed at least every 25 meters (82 feet) along the tunnel wall. These signs should include the running symbol and “EXIT” text, with the addition of a tailed directional arrow and the distance to the nearest exit in feet (see Figure 2). If exits are located in two directions relative to the location of the sign, two signs should be placed side by side to indicate the directions and respective distances to the two exits.



Figure 2. Sample exit directional sign formats.

- **Exit Door Markings.** The area around each exit door should be illuminated at a level that is three to five times brighter than the illumination of the adjacent walls. In addition, exit doors should be marked with strobe lights that activate only during an emergency. The lights should strobe at a frequency of between 1 Hertz and 2 Hertz; white strobe lights are specified under current NFPA guidelines, though further research may be warranted to compare white versus green strobe lights (recommended by some international guidelines) for this purpose.
- **Exit Door Audio Beacons.** Auditory beacons may be used to supplement (not replace) illuminated exit door lighting. When used, auditory beacons should only contain a single message, such as “exit here” or “refuge shelter,” and may be in more than one language in addition to English. The primary benefit of an audible exit door beacon will be realized in the area close to the door. The decibel level used for the beacon should be calibrated to be audible to listeners within a relatively short radius of the door itself, and the use and type of auditory beacons should take into account the specific acoustic characteristics of the location in which it is used.
- **Exit Path Markings.** Exit path markings can be static or dynamic. If feasible, path markers should indicate a direction to an exit door. This may be accomplished with a dynamic light array, controlled automatically or manually by tunnel operations staff, that lights sequentially to indicate a direction. If directional/sequential LED arrays are not a feasible option, LED lights that can be activated to flash in unison during emergency situations seem to be slightly more effective than steady-state lights for indicating an emergency exit path. Path direction to exit doors can also be accomplished with static

markers that include a directional arrow. Pathway markings should be placed no more than 1 meter (3 feet) above the pathway floor.

- **Emergency Messages.** In the event of an in-tunnel emergency or disruptive incident, it is beneficial to broadcast a message to drivers if possible, visually and/or audibly. In the case of an emergency that requires drivers to evacuate the tunnel on foot, an emergency message can be especially important for encouraging the evacuation. The message should contain, at minimum, the following pieces of information:
 - A brief statement about the nature of the emergency, e.g., “fire in tunnel” or “vehicle fire ahead.”
 - Direct instructions about the action to take, e.g., “walk to exits” or “leave vehicles, walk to exits,” if evacuation on foot is warranted. An evacuation direction (e.g., upstream of the fire) should be specified, if applicable.

An emergency message broadcast via a dynamic message sign should be no more than two phases long, with a maximum of three lines/three bits of information per phase. Auditory messages may permit slightly longer messages than dynamic message signs; however, both loudspeakers and radio override systems can be problematic in a tunnel environment. Wireless emergency alerts may have potential for delivering emergency messages via driver cell phones.

- **Sign Material and Technology Considerations.** Internally lit, externally lit, or photoluminescent signs are all options for tunnel environments. Sign spacing should take sign luminance and associated visibility distance into consideration. Any sign or marking must be capable of withstanding environmental and traffic conditions in a highway tunnel, as well as tunnel cleaning procedures (or should be capable of being removed prior to tunnel cleaning). This can mean waterproofing the housings around electrical components for internally illuminated signs and selecting water-resistant and corrosion-resistant materials and coatings. Photoluminescent signs should be selected according to the availability of ambient light to charge them.
- **Public Education and Outreach.** Public service announcements and/or other public outreach materials may be useful for educating drivers about safe behaviors associated with driving in highway tunnels, including information about tunnel incident procedures and tunnel emergency exits, such as cross passageways and refuge areas as applicable. This type of advance education may improve the responses of drivers in the event of a tunnel-related emergency and may also predispose them to look or listen for emergency announcements during an incident.

CHAPTER 1. INTRODUCTION

Emergencies such as vehicle crashes, fires, hazardous waste spills, or terrorist activities can be particularly hazardous when they occur inside underground tunnels. Because stopped or trapped vehicles can make it difficult or impossible for emergency responders to quickly reach or respond to an emergency situation in a tunnel, tunnel users must often evacuate themselves. A 2006 scan tour of underground tunnels in Europe found consistent signing in use from country to country for the purpose of directing tunnel users to emergency exits (Ernst et al. 2006). This research project sought to evaluate signs, markings, and auditory messages in order to develop guidelines for use in tunnels in the United States.

The work plan for this project focused on researching three critical issues in order to develop an objective set of guidelines for tunnel emergency exit signs and markings:

1. Determine the messages and delivery methods (visual, audible, or both) that will encourage drivers to leave their cars and exit a tunnel on foot when conditions warrant such an evacuation.
2. Determine the sign graphics and colors, sign messages, marking types and colors, and auditory messages that most effectively lead people to emergency tunnel exits.
3. Determine the most visible sign and marking materials and technologies for dark and smoky conditions.

The project was conducted in four phases. In Phase I, the research team conducted a review of published studies and existing standards pertaining to emergency exit signs and markings, and developed a final research plan for conducting human factors studies. In Phase II, focus group discussions and a simulation of a tunnel environment under emergency conditions were used to measure human response to various signs and markings intended to lead pedestrians safely out of tunnels during emergency situations. A proposed guide for emergency exit signs and marking systems was developed in Phase III. This research report, including the proposed guidelines and an implementation plan for the guidelines, were developed during Phase IV.

CHAPTER 2. BACKGROUND

Vehicle crashes, fires, and other emergency situations pose particular dangers when they occur in long roadway tunnels; the limited space available for vehicle mobility means that a fully or partially blocked travel lane can quickly trap vehicles, and the confined space within a tunnel can also concentrate heat, smoke, or other toxic gases resulting from the incident. An added danger is that emergency responders will be delayed in responding due to the time needed to reach the tunnel and to access the incident scene inside the tunnel, making it necessary for travelers inside the tunnel to evacuate themselves, often on foot. In the absence of emergency responders to provide direction, in-tunnel signs, marking systems, lighting, and/or audible signals must communicate to tunnel users both the need to evacuate and the location of the nearest emergency exits.

HUMAN RESPONSES IN TUNNEL-RELATED EMERGENCIES

Studies of past tunnel emergencies have found that tunnel users often do not act independently to evacuate themselves on foot, instead choosing to remain in or near their vehicles. If and when people do decide to exit a tunnel in the face of a recognized danger, a common tendency is to try to reach the main (vehicular) tunnel portal, rather than emergency exits for pedestrians, which may be nearer. The reasons for these potentially fatal courses of action can include lack of awareness of an unfolding hazard, uncertainty about the appropriate course of action, reluctance to leave the perceived safety of the vehicle, reluctance to abandon property, and (in the case of fire) incorrect assumptions or estimations regarding how quickly the fire and smoke will spread (van Waterschoot et al. 2008, Nilsson et al. 2009).

Lessons Learned from Past Tunnel Disasters

A review of 26 tunnel fires that occurred between 1970 and 2003 found some commonalities in the behaviors and responses of the public. Observations of frequent driver responses to those incidents included the following:

- During an emergency, people have a tendency to wait for information or instruction rather than seeking it out.
- Motorists often do not recognize they are in danger. On an open roadway, stopped traffic or even a vehicle fire is not usually an emergency situation for other vehicles on the road; therefore, motorists without prior education about tunnel fires/hazards may not recognize an unfolding emergency until it is communicated by announcements, message signs, or other signals.
- Drivers are reluctant to abandon their vehicles and personal items.
- The exit that people are most likely to try to reach is the main tunnel portal—that is, the roadway entrance through which they drove into the tunnel. Emergency exits may be missed or disregarded in favor of the more familiar main portal.
- People tend to overestimate the amount of time they have to evacuate during a fire (van Waterschoot et al. 2008).

Several of these observations were tragically illustrated in the Mont Blanc (France-Italy) and Tauern (Austria) tunnel fires in 1999 and the St. Gotthard (Switzerland) tunnel fire of 2001.

The Mont Blanc fire, which began when a truck carrying flour and margarine caught fire inside the 7-mile-long tunnel, resulted in a 53-hour blaze that destroyed 36 vehicles. Of the 39 people who died in the fire, 29 were found still inside their vehicles; others tried to leave but were too late to escape the spread of fire and smoke, or fled to refuge chambers within the tunnel that ultimately failed due to the heat and duration of the fire. The Tauern tunnel fire, the result of a vehicle collision that in turn exploded a truck's cargo of spray paint cans, killed eight people in the initial crash and another four in the fire that followed. The St. Gotthard tunnel fire, which also resulted from a vehicle collision inside the tunnel, resulted in 11 deaths, again including some people who might have been able to escape before the fire spread. In all three cases, the seriousness of the developing fire was not immediately realized by other drivers in the tunnel, particularly those who were farther from the initial accident and could not see what had happened, and so crucial escape time was lost (Jenssen 2007, Eder et al. 2013, OECD 2006).

Laboratory Studies and Simulations

A driving simulation conducted by Netherlands Organization for Applied Scientific Research (TNO) observed the reactions of drivers when they were confronted by an in-tunnel traffic jam followed by approaching smoke. Drivers in the study were provided with one of three different information conditions:

- Drivers in Condition 1 were provided no information on how to respond to the situation shown.
- Drivers in Condition 2 were given an information leaflet containing information on safe behavior in tunnels prior to beginning the simulation.
- Drivers in Condition 3 were provided the same information leaflet prior to the simulation and also heard two messages from a virtual tunnel operator during the simulation. The first of these messages ("Please turn off the engine") was played 2.5 minutes after the simulated traffic accident, which was also 1 minute before smoke appeared in the tunnel. The second message ("Please go to the escape exits") played 1.5 minutes after the first message, which was 30 seconds after the appearance of smoke.

The study's results showed that increasing the information provided to drivers markedly affected their decisions to leave (or to state their intention to leave) the simulated vehicle in response to the unfolding tunnel fire. With no information other than the visual cues shown during the simulation, 65 percent of drivers in Condition 1 ultimately indicated their intention to leave the vehicle, compared to 75 percent of drivers in Condition 2 and 94 percent of drivers in Condition 3. Additionally, the three information conditions influenced the time that drivers took to decide to leave the vehicle. Measured from the time that traffic came to a stop in the simulated tunnel, Condition 1 drivers took an average of 3.16 minutes to leave the vehicle (if they left at all), the average time for Condition 2 drivers was 2.54 minutes, and the average time for Condition 3 drivers was 2.23 minutes. For Condition 3 drivers, this evacuation time equated to approximately 0.23 minutes following the voice announcement (Jenssen 2008).

A similar study in Sweden in 2007 used a simulated emergency scenario in an actual roadway tunnel to examine motorist behaviors when confronted with a tunnel fire, and to assess the influence of various types of evacuation information on those behaviors. The 29 participants in the experiment all drove (as a queue of 29 vehicles) into a dual-bore tunnel in which a simulated accident scene blocked their path. Two and a half minutes after the first vehicle in the

queue stopped, information signs began displaying a message instructing drivers to turn off their engines and evacuate the tunnel, and a prerecorded alarm began providing a similar message in three languages. At the same time, green flashing lights were activated at emergency exits close to the simulated accident site. In this experiment, the 19 participants at the head of the queue (i.e., within view of the accident site) left their vehicles and had reached or were en route to emergency exits before the alarms and flashing lights activated; for this group, seeing others begin to evacuate was a common factor in their decision to do the same. The remaining participants, who were farther back and therefore could not see the accident site, opened their vehicle doors within a few seconds of alarm activation; while these participants found the audio message difficult to understand, nine out of 10 of them cited it as a factor in their decision to leave their vehicle. Some also mentioned the signs as a factor, while others indicated that they did not notice them. The flashing lights at exit doors were seen only by members of this latter group (Participants 20–29); three recalled the flashing lights as being important to their identification of the door, while the others did not (Nilsson, Johansson, and Frantzich 2009).

SIGN AND MARKING COMPREHENSION

Studies of emergency exit way-finding guidance in the literature include evaluations of signs and visible markings and beacons, as well as of audible signals and messages.

In a high-anxiety situation, a person's focus narrows and cognitive ability is reduced. For this reason, it is important to provide simple, straightforward instructions about what to do and where to go in the event of an emergency. Alarms that include specific messages to leave vehicles and exit the tunnel may help to reduce delayed responses; signs and markings that are easy to see and understand can help to direct people to the closest exit (Nilsson et al. 2009, Morley and Corbett 1997). Since most tunnel users cannot be expected to have specific knowledge or training for evacuating themselves from their vehicles and from the tunnel, the guidance offered by signs, markings, and auditory messages must be straightforward and intuitive.

Running man graphical exit signs were tested with airline passengers at Schipol Airport in Amsterdam to evaluate the comprehensibility of graphical sign messages including the identification of the exit door and an indication that an exit door is located to the left or right of the sign. The signs were tested with people traveling to and from all regions of the world to compare comprehension across different nationalities and languages. Comprehension of these graphical signs was above 66 percent for survey participants who were from Western Europe, North America, and Australia/New Zealand; it was lower for participants from Eastern Europe, Asia, Africa, Latin America, and the Middle East (Morley and Corbett 1997).

In a similar comprehension study conducted by the Federal Aviation Administration, approximately 50 percent of study participants correctly identified the meaning of the running man symbolic exit sign when the sign was viewed in isolation, compared to 97 percent who correctly identified the meaning of a text EXIT sign; symbolic signs indicating the direction to an exit were correctly identified by about 43 percent of participants. When the signs were viewed in context (pictures showing exit doors from the interior of an airplane), comprehension of signs using the running man symbol rose to an average of 70 percent. The study concluded that the symbolic exit signs were not equivalent to the traditional (in the United States) EXIT text sign and would need "additional compensating factors" to provide an equivalent level of safety for people needing an emergency exit (McLean and Corbett 2007).

A series of experiments in Sweden testing exit markings for tunnels found that green flashing lights at exit doors, particularly lights that activate at the onset of a fire alarm, were the most successful for catching the attention of study participants and communicating the intended “exit here” message. Orange flashing lights were also attention getting, but were more likely to be interpreted by participants as signaling danger rather than a safe exit (Nilsson 2009, Ronchi et al. 2012).

A 2013 tunnel evacuation study compared the effects of five different combinations of emergency exit markings on participants’ evacuation speed and exit choice within a smoke-filled tunnel. The test exit door treatments included the following combinations:

1. A backlit emergency exit sign.
2. The exit sign plus green flashing lights on either side of the door.
3. The exit sign, a non-flashing white halogen light above the door, and non-flashing green and white lights on either side of the door.
4. The exit sign plus a loudspeaker that broadcast an audible signal/message instructing participants to exit at that location.
5. The exit sign, plus all of the light options from Scenarios 2 and 3 (white halogen light above the door, green flashing lights on either side of the door, green and white non-flashing lights on either side of the door).

The five different exit treatments did not, in general, change the frequency of correct exit selection when participants were on the same side of the tunnel as the exit door. Under Treatment Conditions 1, 2, 4, and 5, the designated emergency exit was successfully found by 100 percent of the study participants whose starting point in the tunnel was on the same side of the tunnel as the exit door. However, for participants who started on the opposite wall of the tunnel (meaning that they would have to cross the width of the tunnel to reach the exit door), exit door treatments became more significant, with the green flashing lights and the audible signal producing more consistent results than the exit sign alone or the exit sign with any of the steady-state lights. In Treatment Condition 3, the steady-state white and green lights actually deterred a few participants from approaching the exit door from either the same or the opposite wall. Statements made by participants indicate that some thought the arrangement of green and white lights represented the outline of a train rather than an exit door (Fridolph et al. 2013).

VISIBILITY OF SIGN AND MARKING TECHNOLOGIES

Signs and markings intended to guide tunnel users on foot to exits in the event of an emergency must be visible to pedestrians under potentially adverse viewing conditions, including darkness and smoke. Because some types of tunnel-related emergencies may affect electrical systems, emergency signs and markings should be able to operate at least temporarily on independent power sources, or operate without the need for electrical power (e.g., photoluminescent materials).

A series of studies on visibility of signs through various types of smoke found that the smoke density, light scatter off smoke particles, and brightness and contrast threshold of the sign were the most significant factors determining how far away the sign could be seen. However, smoke’s irritant effects, especially at higher densities, also affected visibility. Tests found that visibility distance of a given object in non-irritant smoke was a linear function of smoke density, and visibility dropped off sharply and non-linearly in irritant smoke (Jin 1997). An earlier study

also examined the effects of sign luminance on visibility through smoke, finding that smoke had to reach an optical density of between 0.07 and 0.16 od/m to obscure signs with average luminances over 70 cd/m²; signs with lower average luminances were obscured at lower smoke densities (Collins et al. 1992).

A study comparing laser diodes, xenon discharge tubes, and high-intensity LEDs as visual beacons for tunnel evacuations found that high-intensity LEDs provided the best visibility through smoke. A subsequent emergency evacuation guidance system was developed that used high-intensity LEDs configured as a flashing arrow to indicate the direction of an exit (Ellis et al. 2008). Similar systems have been implemented in Austria, coupled with LEDs to highlight the exit doors themselves. LED beacons, markings, and illuminated signs require relatively low levels of electrical power and can be operated using backup battery power if the main power in a tunnel is lost (Eigentler 2006).

A study by the University of Reading in the United Kingdom examined the visibility and legibility of exit route signs for people with visual impairments such as macular degeneration and cataracts. Participants viewed signs under normal lighting and emergency lighting conditions. In the initial data analysis (comparing four out of the total 24 signs evaluated), legibility distances were greater for two LED signs compared to two externally illuminated signs (Cook et al. 2005).

Photoluminescent signs and markings charge via exposure to a light source, and once charged, will glow in the dark. Because they do not need electrical power to operate, they offer a fail-safe in case of a widespread power loss. Another advantage of photoluminescent signs and markings is the ability to mount them completely flush to a wall, unlike powered signs or lights. Photoluminescent signs have been adopted in Canada for building exits and are required by city ordinance in New York for buildings over 75 feet tall (Carss 2010, Windle 2005). Photoluminescent materials can fail to fully illuminate, however, if they are inadequately charged by ambient light; some types may also degrade with exposure to ultraviolet radiation or moisture (Amy 2008).

AUDIO BEACONS AND MESSAGES

Auditory beacons can provide guidance in poor visibility conditions and for visually disabled pedestrians; they can also help to attract attention to emergency exits even when visibility is good. A study of an emergency evacuation system for mine workers, however, found that auditory beacons used alone as a way-finding system resulted in slower walking speeds and longer evacuation times than auditory beacons coupled with visual beacons (14). In two studies conducted by Boer and Wijngaarden, auditory beacons that included a chiming sound followed by the words “exit here” resulted in significantly more test participants following the correct route to a designated exit, compared to auditory beacons that used a nonverbal sound only. Participants also walked more rapidly toward the self-explaining auditory beacon than they did toward a nonverbal sound (Boer and van Wijngaarden 2004, Boer and van Wijngaarden 2008).

A series of studies by Lund University in Sweden examined how emergency exit messages should be formulated and conveyed in order to facilitate efficient egress. In the first study, customers at IKEA in Gothenburg were presented with spoken emergency exit messages and then questioned about the messages they had heard. Next, an experiment was conducted at the University of Lund with three selected types of verbal messages. The study was conducted with uninformed university students. All trials were video filmed to determine decision and

reaction time to the messages. Both artificial and natural speech were used, with no notable difference in comprehension. The study noted that the artificial voice was very close to a natural voice in sound (Nilsson 2006).

Results of these two studies indicated that people remember less of the important information from a message if the message is too long. Based on the results, it is recommended that messages should not contain more than five information bits. One information bit is in this case a series of words that together build a single concept. Another finding is that people want to know the reason for the alarm. Since the initial phase of the emergency egress is characterized by indecision and information search, it is recommended to include a reason for the alarm in the speech message. Further, hearing that there is a fire leads to less misunderstanding. Hence, it is recommended that “fire” be included in the verbal message.

Comprehensible loudspeaker announcements contribute to proper motorist behavior in the event of fire and other road tunnel incidents. This is especially important for enabling self-rescue but also to ensure smooth traffic flow in case of traffic accidents, vehicle breakdowns, or other closed or blocked lanes. A research study in 2011 found that audible beacons using synchronized longitudinal sound resulted in considerably better speech comprehension inside tunnels compared to previous sound beacon technologies. This technology has been selected for use in highway tunnels in Germany; acoustic beacons using synchronized longitudinal sound are already installed in 10 German road tunnels. Further research is needed in order to develop and improve electro-acoustic sound beacons in tunnels even further. Topics that the 2011 study identified to be explored further included the following:

- Efficient adaptation of sound volumes to changing noise levels.
- Inclusion of escape ways and portal zones.
- Delivery of speech announcement text.
- Standardized ergonomic operation of speech announcements (Mayer et al. 2011).

EXISTING STANDARDS FOR TUNNEL EMERGENCY EXIT SIGNS AND MARKINGS

A number of existing standards in the United States and elsewhere in the world address requirements for emergency exits and associated signage, markings, and audio signals. Some of these are specific to highway tunnels, while others were developed for building exits but may have application, with or without modification, to the highway tunnel environment. Directive 2004/54/EG of the European Parliament establishes minimum safety requirements for all roadway tunnels on the Trans European Roadway Network that are longer than 500 meters. One of the objectives of the guidelines is to improve conditions for self-rescue from a tunnel in an emergency, including guidelines for evacuation lighting and signing.

The National Fire Protection Association is a nonprofit organization with members from nearly 100 nations. As part of its mission, NFPA has developed approximately 300 codes and standards for mitigating the risk and effects of fires. Two NFPA codes that directly address emergency exit signs and markings for highway tunnels are NFPA 502, *Standard for Road Tunnels, Bridges, and Other Limited Access Highways*, and NFPA 170, *Standard for Fire Safety and Emergency Symbols*.

The International Building Code’s guidelines do not directly apply to exit door and exit pathway signs and markings in tunnels; however, they represent a standard for exit signing in buildings that is consistent and recognized throughout the United States.

The following sections summarize guidelines from these and other U.S. and European standards for emergency exit signs, markings, lighting, and audio signals.

Exit Sign Formats and Graphics

Symbolic signs showing a running man exiting through a door were adopted for use in Europe in 1985 (Ernst et al. 2006, Turner 2010). The use of pictograms to replace text for emergency exit and other signs began to gain momentum across Europe in the early 1990s. Since that time, more than one version of a running man pictogram has been in use for exit signs across Europe. The International Organization for Standardization (ISO) 3864 (27) established one version of the pictogram as the standard for fire exit/escape signs, and this pictogram has also been adopted in ISO 7010, which provides guidelines for graphical symbols and colors for safety signs in general. The ISO 7010 exit sign, established in 2013, is a green sign with “EXIT” in white lettering in front of a man running into a door (see Figure 3).

A version of the running man symbol is the recommended exit sign format in Directive 2004/54/EG, Annex III. NFPA 170, Chapter 4, “Symbols for General Use,” provides guidance concerning the shape, colors, and use of symbols for general fire safety information. Table 4.2, “Symbols for General Use”, includes exit door signs and directional signs that incorporate the ISO 7010 running man symbol. Annex A, Section A.12.6.8 of NFPA 502 references this recommendation of NFPA 170.



Figure 3. Running man exit symbol, from ISO 7010.

Sign Size

Several national and international standards provide guidelines for the sizes of exit signs and/or sign elements. NFPA 101 recommends a minimum character height of 6 inches for text EXIT signs. The Norwegian Public Roads Association Standard for Road Tunnels recommends a 400 mm by 400 mm (15.75 inches square) running man symbol sign for tunnel exit doors. IBC requires “EXIT” letters that are at least 6 inches tall and 2 inches wide (with the exception of the letter “I”), with a stroke width of at least 0.75 inches. Finally, British Standard 5499-4:2000 provides the equation $D = hZ$ for calculating minimum sign height and minimum letter height for running man exit path signs, where:

- D = maximum viewing distance in meters.
- h = overall height of the sign’s printed area in millimeters.
- Z = a distance factor based on the illumination of the sign and the level of detail included in the sign’s legend. For exit path signs with the running man symbol, Z is generally assumed to be 170.

Sign Placement

Annex III of Directive 2004/54/EG requires directional signs (running man exit symbol, directional arrows, distances in meters) to be placed every 25 meters (82 feet) along the tunnel wall, pointing to the two nearest emergency exits; the prescribed height of the signs is between 1 and 1.5 meters (between 3.3 and 4.9 feet) from the walking surface.

NFPA 502, Section 7.15 similarly prescribes that directional signs be placed every 25 meters (82 feet) or less on the side walls of a tunnel to indicate the distances to the two nearest exits. While the height of these signs from the ground or path is not specified, the guidelines state that the mounting height should take into account the signs' visibility during a fire.

Sign Luminance and Visibility

Section 12.6.8 of NFPA 502 prescribes minimum illuminance levels for externally illuminated exit signs (5 foot-candles) and minimum luminance levels for internally illuminated exit signs (2.5 foot-lamberts). IBC requires that exit signs must be illuminated at all times, and that they have their own power source that is not dependent on the main power for the building or structure and that will keep the signs illuminated for at least 90 minutes in the event of a main power failure. Like NFPA 502, IBC requires that externally illuminated exit signs must be illuminated at an intensity of at least 5 foot-candles or 54 lux.

While NFPA 502 does not mention photoluminescent signs, NFPA 101 requires radioluminescent or electroluminescent signs to have a minimum luminance of 0.06 fL or 0.21 c/m² (37). ASTM Standard E 2072 similarly provides minimum luminance requirements for photoluminescent safety markings:

- In laboratory testing conditions:
 - 20 mcd/m² after 10 minutes in the dark.
 - 2.8 mcd/m² after 60 minutes in the dark.
- On site (4-inch-wide safety marking):
 - 15 mcd/m² after 10 minutes in the dark.
 - 2.2 mcd/m² after 60 minutes in the dark.

Emergency Exit Path and Door Lighting

Directive 2004/54/EG requires general safety lighting to provide a minimum level of visibility in case of a power outage, as well as evacuation marker lights placed at a maximum height of 1.5 meters (4.9 feet) above the floor to help guide pedestrians who are evacuating the tunnel.

CIE 193-2010, *Emergency Lighting in Road Tunnels*, also provides guidelines for emergency lights and markings for pedestrians in highway tunnels. Section 2.3 of this standard sets the maximum height of evacuation-route pathway markers at 1 meter (3.3 feet) above the carriageway, with a maximum spacing of 10 meters (33 feet). Pathway markers may be permanently illuminated or activated only in the event of an emergency. CIE 193-2010 also provides detailed guidance regarding the illumination and marking of emergency exit doors, intended to encourage vehicle drivers and passengers to leave vehicles and exit on foot if needed. Exit door illumination is intended to make the doors visible and conspicuous to tunnel users at all times (not just during an emergency); CIE guidelines prescribe a doorway illuminance level

three to five times higher than the average illuminance of the surrounding walls, extending out from the door frame for 2 meters (approximately 6 feet) in all directions. Exit door markers are lights intended to act as signals to tunnel users during an emergency; the guidelines recommend flashing green marker lights arranged around the exit door that are activated only in emergency situations. Recommended minimum intensity of the green marker lights is 150 cd, and recommended flash rate is from 1 Hz to 2 Hz.

NFPA 72, *National Fire Alarm and Signaling Code*, Section 18.5.3, recommends the same flash rate (1 Hz to 2 Hz) for emergency strobe lights but recommends white or clear lights rather than green.

Audio Signals

NFPA 72 provides guidance for audible alarms and evacuation messages for buildings, some of which may have some application for audible alarms and verbal messages in tunnels. Section 18.4 establishes auditory requirements for evacuation signals, including sound levels and signal characteristics. Some of NFPA 72's recommendations that may inform audio signal recommendations for highway tunnels include the following:

- Section 18.4.1 establishes maximum sound pressure levels from the combination of ambient noise with the sounds created by audio signals. Maximum peak sound pressure is limited to 110 A-weighted decibels (dBA) and maximum average sound pressure to 92 dBA.
- Section 18.4.2 describes a three-tone temporal alarm used to notify building occupants to evacuate.
- Section 18.4.3 establishes minimum sound level requirements for public-mode audible signals as 15 dB above the average ambient sound level.
- Section 18.4.6 outlines procedures for calculating minimum sound pressure levels needed to overcome a particular masking noise and may be applicable to certain emergency situations in tunnels, such as when jet fans are activated for ventilation.
- Section 18.4.7 provides recommendations for audible signals at exit doors.
- Section 18.4.10 describes voice intelligibility requirements for voice messages.

NFPA 502 Annex B, Section B.2.5 specifies maximum peak noise levels along highway tunnel evacuation paths of 115 dBA and maximum average levels of 92 dBA. This represents a 5 dBA increase in the maximum peak-level sound pressure specified in NFPA 72 for buildings, while the maximum average sound pressure is the same for both standards.

EXPERT INPUT

Input was sought from experts in roadway signage, tunnel operations, and emergency response at various points throughout the project. First, members of the Regulatory and Warning Signs Technical Committee (RWSTC) of the NCUTCD were asked for their input regarding emergency exit signs and markings. Next, a subject matter expert (SME) panel of experienced tunnel facility responders in the law enforcement, fire/EMS, department of transportation (DOT), towing and recovery, and traffic incident management communities was assembled via WebEx on June 26, 2014, to discuss practices and experiences pertaining to tunnel incidents and emergencies. Finally, some additional tunnel operators were interviewed via telephone in

February 2015 regarding their emergency procedures, including communication to tunnel users. Table 1 lists the tunnel facility experts who provided input to this study.

Table 1. Participating Subject Matter Experts.

Participant		Agency/Committee	Title
NCUTCD	Bruce Ibarguen	Maine DOT	State Traffic Engineer
	Tom Heydel	Wisconsin DOT	Regional Traffic Engineer
	James Pline	Institute of Transportation Engineers (ITE)	Past ITE President
SME Panel	Michael Fitzpatrick	Massachusetts DOT	Highway Operations Center Manager
	Lorenzo Parra	Massachusetts DOT	Director of Highway Operations Center
	Lt. Dave Cain	Pennsylvania State Police	Commander, Central Patrol Section/Troop T, Everett
	Allen Baldwin	Winchester, VA Fire Department	Fire Chief
	Rusty Fitzhugh	Virginia DOT	Hampton Roads Bridges and Tunnels (HRBT) Operations Manager
	Tina Eley	Virginia DOT	HRBT Operations Supervisor
	Lisa Williams	Virginia DOT	Field Supervisor
	Eric Roberts	Virginia DOT	Field Supervisor
	Lynn Manges	Interstate Emergency Services, Towing and Recovery, Bedford, PA	Director of Towing Operations
Interviews	Todd Anselman	Colorado DOT, Hanging Lake Tunnels	Electronics Specialist
	Spencer Dickey	Colorado DOT, Hanging Lake Tunnels	Tunnel Operations Manager
	Douglas Haight	Washington DOT (WSDOT), Seattle Tunnel	WSDOT Project Engineer, Sound Transit Projects
	Chris Thomas	Washington DOT, Seattle Tunnel	Supervisor of Tunnel Operators

The following sections summarize the input received from the interviews and panel discussion.

Driver Responses to Tunnel Incidents

Many drivers view car fires and other potentially hazardous incidents in tunnels as just another traffic slowdown. Because sightlines in tunnels can be shorter than on open roadways,

motorists may not even know what the incident is until or unless they are close to it. Frustration and anger are prevalent behaviors; drivers do not want to get stuck in an incident inside of a tunnel. A risky behavior that has been frequently observed is drivers speeding past the incident on their way out of the tunnel, risking everyone on the scene as well as themselves. Sometimes the opposite occurs, with drivers slowing down close to an incident to rubberneck, particularly drivers who are not accustomed to traveling in tunnel facilities.

When all lanes are blocked, motorists will sometimes exit their vehicles and linger around either in the tunnel tubes or on the surface prior to the incident. This causes the potential for further injury. The likelihood of additional incidents increases if traffic is diverted to other tunnel bores at crossings.

Emergency Procedures

Many tunnels have ventilation systems that are activated in response to events involving smoke or other hazardous materials. When this occurs, all tunnel areas upstream of the incident (where the stopped traffic sits) are put into positive pressure. Exhaust fans activate downstream of the event, removing smoke and gases through the end of the tunnel and up vent building stacks. Motorists downstream of an incident do not tend to linger; they continue out of the tunnel.

Advanced monitoring and incident management systems are becoming more common in newly constructed or refurbished tunnels. These systems can include video and thermal cameras to enable operators to see the exact location and nature of an incident, including the presence and extent of smoke, and can automate response sequences including the activation of emergency signs and markings.

Emergency Announcements and Exit Guidance

Planned and rehearsed strategies are important for clearing in-tunnel incidents quickly. Communication with the motorists approaching the incident is very important in allowing the opportunity to divert, if possible. On-scene temporary traffic control for intermediate and major incidents is one approach to this problem, and several of the agencies represented by the expert participants have developed and practiced procedures for getting first responders on scene as quickly as possible.

The represented agencies also use a variety of other techniques for communicating with drivers during an incident, including dynamic message signs, strobe lights at exit doors, and static signs; one agency also sends alerts out via Web feed and Twitter. A radio override system is in use at the Seattle Tunnel. Issues and limitations that the expert participants have experienced with various communication methods include the following:

- Dynamic/variable message signs, some with canned messages and some that can be manually programmed with a customized message, are in use in several of the tunnels represented by the participants. The Seattle Tunnel, as one example, contains some fixed variable message signs (VMSs) for lane control, alternating with VMSs that can display one of 110 preprogrammed messages as needed. The signs can be activated with appropriate messages as part of an automated incident management system that allows a tunnel operator to specify whether an evacuation is advised. The primary limitation of DMSs/VMSs is the short message length.

- Highway advisory radio and radio override systems are older technologies, and many tunnel operations are moving to or considering other options. Many override systems were designed for AM/FM radio frequencies, and with the rising prevalence of satellite radio and smartphone-based entertainment, the number of drivers that are likely to hear messages broadcast via radio override is diminishing. Radio override systems can also bleed into tunnel bores beyond the one affected, potentially causing confusion.
- Loudspeakers are not currently in use in the tunnels represented by the expert participants, due to problems with reverberation and resultant low intelligibility.

Exit Sign and Marking Considerations

Each sign must convey a very specific message. The message must be brief, as the user will be in a stressful situation and will need to interpret the message immediately. Easily recognizable sign legends are important for exit door signs and for signs and markings that will direct the evacuee to the exit doors. Consideration must be given to which exit is nearest to the evacuee at any point along the tunnel. Static running man symbols are widely recognized, but a static sign could be pointing toward the hazard.

Assuming that the evacuee is unable to stay in his or her vehicle, emergency exit signs only need to be legible for a walking (or perhaps running) speed. Tunnel lighting is present in most highway tunnels. Therefore, the sign will have some ambient light on it already. However, if the emergency has knocked out power to the lighting, then the signs may need battery backup to allow the evacuee to see them. This would be true if the light were external or internal to the sign.

It will be important to convince people to get out of their vehicles and walk. LED edge markings, similar to those in the aisles of airplanes, could help provide guidance to the nearest exit. It will probably be necessary to have segmented sections of the tunnel with various controls for emergency path markings dependent on where the emergency occurs. An advantage of lighting in or near the pavement is that usually smoke is not as thick near the ground.

Strobe lighting is being used in some tunnels to identify exit doors, but more research may be needed to determine whether people interpret strobe lighting to mean “come this way” or “do not come this way.”

Signs and markings need to be able to withstand environmental and traffic conditions within a highway tunnel, as well as tunnel cleaning procedures (or should be removable during tunnel cleaning). Tunnel cleaning can involve pressure washing with water and/or rotating brushes.

Current U.S. tunnel designs and types of exits should be considered when recommending sign placement. To know what to develop for a sign layout, it is necessary to know where and to what the evacuee is being sent.

CHAPTER 3. FOCUS GROUPS—RESEARCH APPROACH AND RESULTS

Two focus groups were conducted with drivers to gain a better understanding of how tunnel users might respond to various tunnel incident scenarios and warnings.

Focus group discussions were held on June 12, 2014, in a conference room at the Texas A&M Transportation Institute (TTI) office in Houston, Texas. The first group met at 1:00 p.m., and the second group met at 5:30 p.m. Each session lasted approximately 70 minutes. The demographics of the focus group participants are shown in Table 2.

Table 2. Focus Group Participant Demographics.

Group 1		Group 2	
<i>Gender</i>	<i>Age</i>	<i>Gender</i>	<i>Age</i>
M	23	M	20
M	54	M	41
M	61	M	56
M	64	M	58
F	18	M	68
F	22	F	20
F	24	F	25
F	27	F	39
F	43	F	56
F	53		
F	62		

PROCEDURE AND RESULTS

A PowerPoint presentation was used to present the groups with pictures, video, and audio as stimuli for the discussion questions. Each of the moderated discussions began with an introduction by the moderator about focus group protocol and etiquette, followed by some icebreaker questions to give participants a chance to introduce themselves and to become comfortable participating in the discussion. Participants were asked to tell the group their first name, whether or not they had experience driving in tunnels, and (if applicable) what they liked best or least about driving in tunnels.

Of the 11 participants in Group 1, seven reported having driven through highway tunnels. In Group 2, six out of the nine participants have driven through tunnels. The results are presented in the rest of this section with respect to how the conditions were presented to the focus group participants.

Slowing/Stopping Traffic in a Tunnel

Participants viewed a brief video clip of a vehicle entering a highway tunnel, proceeding a distance into the tunnel, and then slowing as other traffic in the tunnel began braking. Following this video, participants were asked, “If you were driving through a tunnel and traffic slowed or stopped, what would you guess might be the reason?”

Participants in both groups identified possible reasons including ordinary rush-hour traffic congestion, road construction, a stalled vehicle, a traffic accident ahead, and a structural failure within the tunnel.

When asked what their initial reaction would be to this scenario, most participants indicated that they would wait for traffic to start moving again. One participant said that he would turn on his hazard lights to alert traffic behind him that he was stopped, and another said that she would try to maneuver her vehicle to an open space in the adjacent lane and try to keep moving toward the tunnel exit. A few participants indicated that they would feel frustrated or anxious about being stopped inside a tunnel. One or two participants in each group said that they would turn on the vehicle's radio to listen for messages about what was happening in the tunnel, and one participant in Group 1 commented that there should be signs throughout the tunnel to provide real-time messages.

Stopped Traffic, Drivers Exiting Vehicles

Participants next viewed a still photo of traffic stopped inside a tunnel, with some of the drivers outside their vehicles standing or walking. When asked what might be happening in a scenario that looked like this, some participants speculated that there might be something more dangerous or unusual than an ordinary traffic jam farther ahead in the tunnel. Participants in both groups had mixed opinions about appropriate actions to take, with some saying they would want to exit their vehicle to find out what was happening and others believing that leaving their vehicles would place them at additional risk. Some sample comments were as follows:

- *Whatever it is, it's not good. If people are getting out of their cars, it's not good.*
- *But also those people getting out of their cars causes a problem, because once the traffic starts moving, someone might get hit. It's a hazard.*
- *I think it might be dangerous to stay in the car. If something's coming, you might not see it, and then you can't run.*
- *I think I'd get out of my car for a few seconds and stand up, to see if I could see any farther ahead, and get some sort of clue as to what's happening, as to why traffic isn't moving.*
- *I think in this situation, where people are out of their vehicles and talking, at least you're informed as to what is taking place, to put your mind at ease and not panic or get anxious about what's happening.*

While the specific action that participants said they might take varied, most participants agreed that they would be seeking additional information about the situation, such as the following:

- *Signs on the top and sides of the tunnel.*
- *Something similar to the signs you see on freeways, telling you about accidents or delays ahead.*
- *Ideally, the sign would be before you ever entered the tunnel. That way, it can divert traffic, or you can make the decision about whether to wait outside the tunnel or take a different route.*
- *If traffic is backed up, emergency personnel might not be able to get there. [They need] a way to communicate without needing someone to get in to the spot where the trouble is.*
- *[Message via] the radio.*

- *I would get out and try to find out from others who are walking around. Someone's bound to know what's going on.*

Stopped Traffic, Smoke

Participants viewed a still picture showing vehicles in a tunnel surrounded by smoke. Most of the participants identified the haze in the photo as smoke, and some speculated it could be coming from a vehicle fire; one participant in each group thought it might be fog.

Reactions to a possible fire or similar emergency situation varied, with some participants saying that they would leave the tunnel as quickly as possible, on foot if necessary, and others commenting that they would be more likely to seek more information about the situation first. Two participants in Group 1 said that their first action, if they were close enough to see a burning vehicle or similar situation, would be to try to help whoever was in the vehicle or otherwise in immediate danger. Comments about this situation included the following:

- *Get out!*
- *I would ask cars behind me to back up.*
- *If I was close enough to see what was going on and I could possibly help, I think I would try to help.*
- *If I was behind the place in the tunnel where there was a fire going on, then my first reaction would be to get out of there.*
- *[My response] depends on how far it is to get out, and on what exactly is going on. Is there a fire? What kind of fire is it?*
- *[I might not leave] at this point, unless other people are leaving. If I see that others are exiting on foot or running, then I'm going too—I don't know if there are emergency exits or if I'm going all the way back [to the portal], but I'm getting out of there.*
- *The first thing would be to determine if it's smoke or if it's fog. If I smelled something burning, then I would try to exit.*
- *But on the other hand, if you and a lot of other people left their vehicles there, it could hinder emergency vehicles trying to get to the car that's on fire or to the person that's hurt.*
- *The key is signage...[that] could tell you to stay or exit.*

Finally, participants were asked where they would start looking for an exit if they did decide to leave their vehicle and walk. One participant said she would start heading “back the way I came,” indicating the tunnel’s main portal. Others speculated that there might be side doors, with ladders or staircases going up.

DMS Messages

Participants viewed a series of three messages on a simulated dynamic message sign. Each message consisted of two phases, each consisting of a word or phrase that totaled 18 characters or fewer; the phases were animated on the slide so that they alternated on the screen every 2 seconds. This length of message was selected based on a typical DMS width for a two-lane tunnel (according to a tunnel operator and a DMS vendor who were consulted during the preparation of the focus group presentation). Two phases is the maximum recommended by the *Manual on Uniform Control Devices (MUTCD)* for DMS messages. This format was chosen

in part to assess the effectiveness of fairly short messages in conveying useful information and an appropriate sense of urgency.

“Emergency—Walk to Exits”

The first message tested was “Emergency—Walk to Exits,” displayed in two phases (in the preceding text, the dash separated the two phases). Participants were asked, “What would be your reaction to seeing this message?”

Within Group 1, most participants indicated that they would follow the sign’s instructions. In Group 2, some participants said they would immediately follow the instructions, but others indicated that they might be slower to respond. Participant comments included the following:

- *That’s all the information I need.*
- *I would want to know why but would still exit because it says “emergency.”*
- *I’d think “okay, let’s go.”*
- *“Emergency” would slow me down if I was driving.*
- *If it’s at the beginning of the tunnel, I would still be trying to get my car out of there. But if it were in the middle of the tunnel, and traffic is stopped, and this came on, then I’m getting out of the car.*
- *I probably would panic. I would be nervous to walk in the tunnels I’ve been in; I’d be afraid to get hit.*

“Leave Vehicle—Walk to Exits”

The second message tested was “Leave Vehicle—Walk to Exits.” Participants were again asked, “What would be your reaction to seeing this message?” Participants were also asked whether this message provided them with more or less useful information compared to the first message.

While some participants appreciated having the “leave vehicle” directive prior to “walk to exits,” most felt that receiving instructions without a reason being provided was less informative overall. Participants who preferred “leave vehicle” to “emergency” felt that the two-part directive provided extra guidance that might be useful in a stressful situation and also conveyed the message that leaving in a vehicle was not possible; participants who preferred “emergency” as the first part of the message felt that it was more important to provide context for the “walk to exits” command. Participant comments included the following:

- *I’d be suspicious [of “leave your vehicle”]. Why do I need to leave my vehicle? What are you trying to do?*
- *Not enough information.*
- *“Emergency, walk to exits” is better for me. The word “emergency” sticks out.*
- *I’d probably keep driving until I see more information rather than just leave my vehicle. Would like information that tells me the next step, like “get out and walk.”*
- *It gives specific commands. The other one just said “emergency,” so if I was driving I might slow down, but this one says, “Leave your vehicle, there’s a major problem.” Which means I’m going to leave my vehicle, I’m not going to question it.*

- *I would say that the “leave vehicle” is better for me; I see that word “emergency” and I’m scared. “Leave vehicle” doesn’t get me excited or upset, where “emergency” might make me anxious.*

“Fire in Tunnel—Walk to Exits”

The third message tested was “Fire in Tunnel—Walk to Exits.” This was the least preferred message among both groups of participants. Participants expressed concern that seeing a “fire in tunnel” message might cause anxiety or panic that would impede safe evacuation. Comments on this message included the following:

- *Here’s my initial reaction to that: mayhem. I don’t think people would see that and walk to the exits. I think people would freak out and would run instead of walking. I would much prefer “leave vehicle” or “emergency” to “there’s a fire” because a bunch of people are going to freak out and run for the exits.*
- *As long as I’m being cautioned to get out of harm’s way, I can find out what happened after I’m safe.*
- *This is definitely my least favorite. It’s informative, which is awesome, but I would be more anxious, and nervous, and more inclined to run if this was the sign.*

In the following portions of the discussion, however, some participants expressed support for the specific hazard information provided by the phrase “fire in tunnel.”

Preferred Phrases

Participants viewed a list of phrases that could be used in a DMS message and asked which phrases they felt would be the most useful to include in a message advising drivers to evacuate a tunnel on foot. Phrases shown included “Emergency,” “Fire in Tunnel,” “Turn off Vehicle,” “Leave Vehicle,” “Walk to Exits,” and “Exit on Foot.” Participants were also invited to modify these phrases or add different phrases to the list.

Nearly all participants agreed that “Walk to Exits” or “Exit on Foot” was an essential phrase. Participants were split on whether a description of the situation (e.g., “emergency”) or a supplemental command statement (e.g., “turn off vehicle” or “leave vehicle”) was more important to include; a slight majority preferred knowing something about the situation as a reason for the “walk to exits” or “exit on foot” directive. While most participants were still opposed to using “fire in tunnel” as the situation description, one participant supported its use. Participant comments included the following:

- *NOT “fire in tunnel.” The others are okay. I think “turn off vehicle” and “leave vehicle” are implied already by “walk to exits.” If there’s not an immediate need to leave (maybe an incident ahead but not an emergency), then “caution,” maybe even “stay in your vehicle” in that case. “Accident ahead, stay in vehicle.”*
- *Even though it would cause the most panic, I would like “fire in tunnel, walk to exits” if there really is a fire in there. I don’t want to be strolling through, not hurrying because I don’t know how dangerous it is. If there’s a fire, I would want to know right away before things start blowing up. If there is a fire, that information is essential, then after that “walk to exits.”*

- *“Turn off vehicle” because people in a panic would likely forget to do that and it could cause problems like a buildup of carbon monoxide, then “walk to exits.” That would get my attention.*
- *“Walk to exits” is most important. “Leave vehicle” is also good, because it means that the situation is urgent.*
- *I like “exit on foot” because it tells you that you can’t go in your car.*
- *They should go hand in hand. You need the situation plus the command so you don’t think you can stay in your vehicle if you shouldn’t. “This is what’s happening, now this is what you do.” That cuts down on the likelihood that you’ll panic, and you’ll know how to react. Is it giving me an option to leave, or telling me I need to leave now?*

Audio Announcement

Participants listened to a recording of the following voice announcement: “Attention—there is a fire in the tunnel. Turn off your engine, leave the keys in your vehicle, and walk to emergency exits immediately.” Reactions to the announcement were slightly different between the two groups. In Group 1, most participants indicated that the announcement would encourage them to leave, though most said that they would not leave their vehicle keys behind and questioned the reason behind that request. As with the DMS announcements, some participants were opposed to specifying a tunnel fire as part of the announcement, rather than a more general “emergency,” but others supported the more specific description to convey the urgency of the situation. One Group 1 participant commented that the announcer’s voice was too emotional and could increase anxiety.

Comments from Group 1 participants about this message included the following:

- *Don’t say “fire in tunnel.”*
- *If you’re told to get out of your car and leave your keys, you want to know why.*
- *If there’s a fire, in most cases you won’t die from the fire, you’ll die from the carbon monoxide. If it says “fire” people know they could die so they will leave. Damn the car! The car and the keys aren’t going to do any good if you die.*
- *Need a calmer announcer’s voice. The announcer should not be sounding like he’s panicked. If he’s panicking, I’m going to panic.*
- *So maybe they should tell you, very calmly, that there’s a fire in the tunnel and you need to leave now. Take your keys, leave your keys, whatever, just leave.*

The reaction to the announcement among most Group 2 participants was more skeptical. They also questioned the request to leave vehicle keys behind, to the extent that some expressed their suspicions about the motivation of the entire announcement. The perception of the tone of the recorded announcement was also different than in Group 1; a Group 2 participant commented that the announcer’s voice was too monotone and needed more urgency to make the message believable. Overall, the participants in Group 2 indicated much more resistance to leaving their vehicles and exiting based on the information provided in the voice announcement. One older male in Group 2, however, commented that the mere fact that an emergency was important enough to warrant an announcement should be enough of a reason to pay attention to it.

Comments from Group 2 participants about the audio message included the following:

- *I would turn off my car and exit the tunnel, but I wouldn't leave my keys. I'm always skeptical; if it's coming over a loudspeaker it could have been hacked, they could be trying to steal my car. If I can't see smoke, I'm definitely not leaving my keys.*
- *Asking me to leave my keys now has me questioning the whole message. Had you just said "cut off engine, head to doors" I would pay attention. But because you're now asking me to leave my keys, I want to know what's going on.*
- *"Leave keys" is a red flag for me.*
- *Usually you don't hear an announcement or see something displayed unless there's an emergency... We may not know exactly what's going on, but the alarm says there's something happening. You don't know the degree of emergency, but something's happening or the alarm wouldn't be sounding, so beware.*

Other comments received in the two groups about emergency messages and delivery included the following:

- *Maybe use a scale for the urgency of the problem, like the hurricane rating system. "This is how much panic you should have, this is how much urgency."*
- *Provide the message in different languages, not just English.*
- *If I'm in a strange city and I don't know how long the tunnel is or where the exits are, other than the one behind me, I'd like something to tell me where the exit is.*
- *Say which exit to take.*
- *Hearing the announcement is better than seeing a flashing message.*
- *Should have a combination of signs and audio. If someone's playing music, they could miss an audio announcement.*

Leaving Vehicle and Subsequent Actions

Participants were asked, "Would you take your car keys?" and "What other items would you try to take with you?" Nearly all participants indicated that they would take their car keys, most of them simply due to habit or because of the time delay involved in detaching a vehicle key from the rest of their keys. Two participants (both in Group 1) said they might leave the vehicle key so that emergency crews could move their vehicle if needed. Other items that participants indicated they would try to take included purses/wallets, phones, and personal/medical items. Two participants talked about taking children who were in the car, and one commented that if children were present, keeping calm and avoiding panic would become even more important.

The next question was, "If you saw other people who were staying in their vehicles, would that affect your decision to stay or leave? Would it change your actions in any other way?" Among the Group 1 participants, responses were very consistent: everyone in the group agreed that if there had been an announcement to leave, seeing other people still in their vehicles would not change their own decision to leave:

- *I would probably knock on their window and say, "It says to get out."*
- *If they didn't want to leave, I wouldn't waste my time and put myself in danger.*
- *I would encourage those people to leave, but I wouldn't stay there and argue with them.*

In Group 2, reactions were mixed, with some participants expressing more of a tendency to follow the lead of other drivers, and others opting to leave if prompted by warnings/announcements regardless of what others were doing:

- *If I saw that other people were staying in their vehicle, I would probably stay in mine. Worst-case scenario, I'd leave my car.*
- *I would go with the majority (if staying or leaving).*
- *I probably wouldn't walk as fast, if other people were staying. I would try to feel out the situation, question it more, but if everyone else is running towards exits I'd get out. I might walk toward the exit, but try to keep figuring out what's going on, maybe not go through the exit just yet.*
- *I would follow instructions given by sign or audio. They can't give you all the details about what's happening, but you need to follow directions or deal with the consequences.*
- *Here in Houston, we deal more with sudden flooding. There were people staying on the freeway during Hurricane Allison when the water was rushing toward them. If you hesitate for a few minutes, you could lose your life, so better safe than sorry. It's common sense.*
- *If there is a fire in a tunnel, you know it affects oxygen, so no matter what others are doing, if you know there's a fire, get out!*

Follow-Up Questions and Other Comments

Participants were asked if they had other suggestions or questions regarding emergency signs or announcements in highway tunnels. Most of the suggestions received were for signs pointing the way to emergency exits, and for lighting strategies to indicate emergency situations. Participant comments included the following:

- *Post emergency signs at intervals (maybe every mile or mile and a half) throughout the tunnel.*
- *Put DMS signs every 200 feet letting you know where next exit is.*
- *Directional signs to exits would be helpful, spaced pretty closely so that you don't miss seeing a sign that could show you the way out. I think lighted signs would be best.*
- *I'd think you'd want phosphorescent signs, in case of loss of power.*
- *Maybe use lights to provide visual color coding as you get closer to the incident (green if there's no problem, yellow if there's a problem ahead, then red as you get close to where the danger is).*
- *Red and flashing lights are best [to indicate an emergency].*
- *More than anything, flashing lights get your attention, so maybe something that only flashes during an emergency situation would help me know that there's something wrong. If I'm driving and see something flashing, that's a sign to me to slow down, survey the surroundings. Words are good, but you can't always see them; you can always see something flashing.*
- *Use multiple languages; we have all languages here now.*

As follow-up questions, participants were shown examples of some symbols for emergency signs such as the running man exit sign, a text EXIT sign, emergency telephone, fire extinguisher, disabled-access refuge point, and the running man symbol with a directional arrow

and distance. Participants comprehended nearly all of these symbols without hesitation; there was some discussion about whether the refuge point sign indicated an exit, but most participants agreed that it probably indicated a safe place for people with disabilities to stay during an emergency until emergency responders could reach them.

When asked if the green running man exit sign and the red text EXIT sign conveyed the same or different meanings, most participants thought that the signs were more or less equivalent. A couple of participants felt that the running man symbol implied more urgency (because he appears to be running for the exit rather than walking), while two other participants felt that the red color of the text sign implied “emergency” more than the green color of the running man sign. However, all participants were confident that both indicated a way out of the tunnel.

FOCUS GROUP CONCLUSIONS

Individual participants’ responses during the discussion were not consistently correlated to age, gender, or prior experience driving in tunnels, except that the participants who had traveled in tunnels frequently were more likely to mention concerns about the confined space in a tunnel if an emergency were to occur (e.g., concerns about vehicle exhaust building up during a traffic jam or about the limited space available for a person to walk alongside the traffic).

While many participants indicated that they would likely consider leaving a tunnel on foot if they saw smoke and/or saw other people exiting, several also indicated that uncertainty about what might be happening or about the safest course of action might cause them to wait for further information or instructions. Even before signs and audio announcements were introduced in the discussion, several participants suggested that information about in-tunnel incidents should be communicated to drivers if possible.

Participants were generally resistant to the idea of leaving their vehicle keys behind, with most of their comments indicating a lack of awareness of why that request would be made. This indicates that public education efforts on highway tunnel safety may need to include an explanation of why emergency responders might need to move vehicles, and/or that an explanation should be included if drivers are requested to leave their vehicle keys behind. There was a range of responses regarding the influence of other drivers’ behaviors on participants’ anticipated actions. In one focus group, there was a general tendency toward acting on provided information/announcements regardless of how others were perceived to be responding; in the other group, some participants weighed the crowd response as a significant factor in their own response. This indicates that public education efforts on highway tunnel safety in general may be warranted.

The emergency messages that the majority of participants found to be most helpful, as well as most likely to provoke the desired response, included an indication about the nature of the incident followed by a direct instruction. Of the instruction phrases presented, “walk to exits” was preferred by most participants, though “exit on foot” was also considered effective. “Turn off engine” and “leave vehicle” were considered to be useful supplemental instructions, but not as important as “walk to exits” for conveying the need to evacuate. The general term “emergency” was preferred over a more specific description such as “fire in tunnel,” due to participants’ concerns about possible anxiety or panic resulting from the term “fire;” however, some participants argued that a more specific description of the emergency would better communicate the urgency for an immediate evacuation.

The focus group results were used to finalize the emergency messages that were tested with participants in the tunnel simulation (described in the following chapter). Because “Fire in Tunnel—Walk to Exits” was parallel wording to the longer planned audio/text/Twitter message, and because earlier feedback from the project panel at the Phase I project meeting was in favor of specifying “fire” when fire is present, the DMS message subsequently tested in the tunnel simulation was “Fire in Tunnel—Walk to Exits.” Also, because of focus group feedback, the audio announcement used in the tunnel simulation included an explanation for the request to leave keys in vehicles.

CHAPTER 4. TUNNEL SIMULATION PROCEDURE AND RESULTS

The tunnel simulation first tested individual responses to a tunnel emergency scenario similar to those discussed by the focus groups, and then tested several sign and marking formats and technologies within the simulated tunnel environment, both for participants' comprehension of and confidence in various formats and for detection and legibility distances through smoke.

The tunnel simulation took place in College Station, Texas, and involved 63 participants. Potential participants included licensed drivers aged 18 and older, both men and women; as with the focus groups, recruiting targeted a mixture of younger, middle-aged, and older adults.

PARTICIPANT DEMOGRAPHICS

A total of 63 men and women from the Bryan-College Station area participated in the tunnel simulation. Participants ranged in age from 20 to 83. Table 3 summarizes the demographics of study participants.

Table 3. Tunnel Simulation Participant Demographics.

Age Groups	Males	Females
20–34	12	13
35–59	6	15
60+	9	8
Total	27	36

STUDY PROCEDURES

The simulation occurred in two stages. Stage 1 was intended to test participant responses to an unfolding hazardous situation in a highway tunnel and to emergency announcements telling them to leave their vehicle and evacuate on foot. Participants were told that the study procedure was examining traffic control devices for highway tunnels but were not told in advance of the simulation exercise that the devices being tested pertained to emergency exits.

Stage 2 of the simulation tested sign and marking formats and technologies for participant comprehension and visibility. The researcher presented each participant with a series of signs, markings, LED beacons, and audio beacons within the smoke-filled chamber, testing the following:

- Detection distance for signs and markings.
- Identification/legibility distance for signs and markings.
- Comprehension/interpretation and preference for sign, marking, and beacon formats.

Figure 4 shows the final layout of the tunnel simulation room. In Stage 1, the participant was seated in the driver's seat of the parked vehicle with the researcher seated in the passenger seat. For Stage 2, the participant and researcher viewed each sign and treatment combination one at a time, using a 60-foot corridor. Ambient lighting was set at 10 lux (measured at floor level), and the chamber was then filled with artificial smoke; the density of the smoke was measured continually and recorded on each participant's data sheet for each sign and beacon option. Having the density of the smoke vary from the beginning to the end of each participant's

testing period allowed for the viewing distances of each sign and marking to be placed in the context of smoke density.

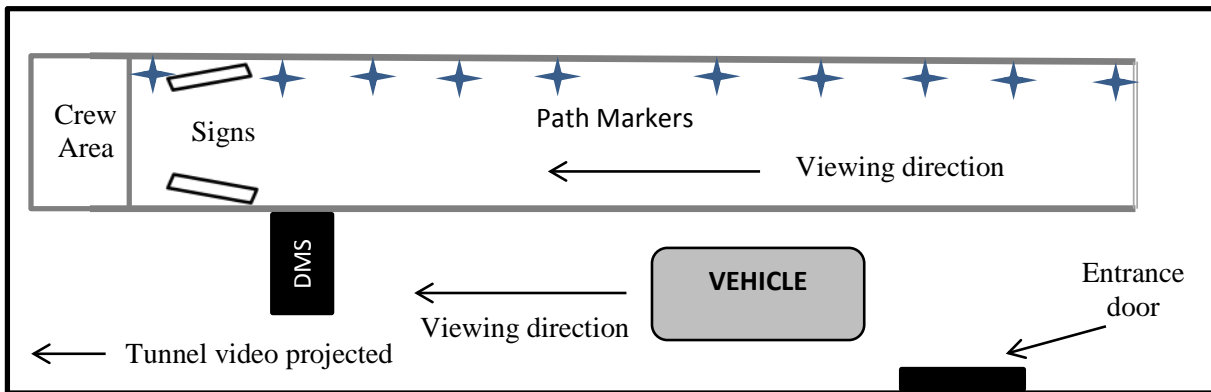


Figure 4. Layout for tunnel simulation.

Participants were divided into six groups, as shown in Table 4. This allowed for three different information conditions in Stage 1 and three different sign orders in Stage 2.

Table 4. Experimental Groups for Tunnel Simulation.

Group	Stage 1—Information Level	Stage 2—Sign Order
A	Ambient cues only	Sign order 1
B	Audio message	Sign order 2
C	DMS message	Sign order 3
D	Ambient cues only	Sign order 3
E	Audio message	Sign order 1
F	DMS message	Sign order 2

Stage 1: Response to Emergency Situation and Messages

The first few minutes of the Stage 1 exercise simulated a trip through a highway tunnel that was stopped by a traffic jam, followed by the appearance of smoke. The purpose of the exercise was to determine what type of message is most effective for encouraging drivers to leave their vehicle and evacuate the tunnel on foot, if such an evacuation is warranted. Participants were divided into three experimental groups (20 to 22 participants in each group) for Stage 1.

The Stage 1 study procedure provided the same introduction to all participants as follows:

- In the intake/preparation room, the greeter told participants that they would be seated in a vehicle, would view a short video clip, and would be asked to execute or describe the actions they would take that they believed were the most appropriate based on what they saw and heard.
- The researcher escorted the participant to the driver’s seat of a parked car inside the tunnel simulation chamber. The researcher sat in the passenger seat of the same vehicle.
- Once the participant and the researcher were seated in the vehicle, the researcher repeated the instructions to the participant, began the video recording of the forward scene, and

played the simulation video. The video was projected on a wall in front of the vehicle to provide a near-full-size image of the simulated trip (see Figure 5). The clip showed a driver's view of a vehicle entering a highway tunnel and then encountering slowing and stopping traffic while inside the tunnel. The end of the clip was edited to show dark smoke streaming into the tunnel from ahead of the driver's vehicle and darkening the view of the tunnel. The soundtrack of the video was also edited to add the sounds of vehicle horns, engines, and a loud ventilation fan.

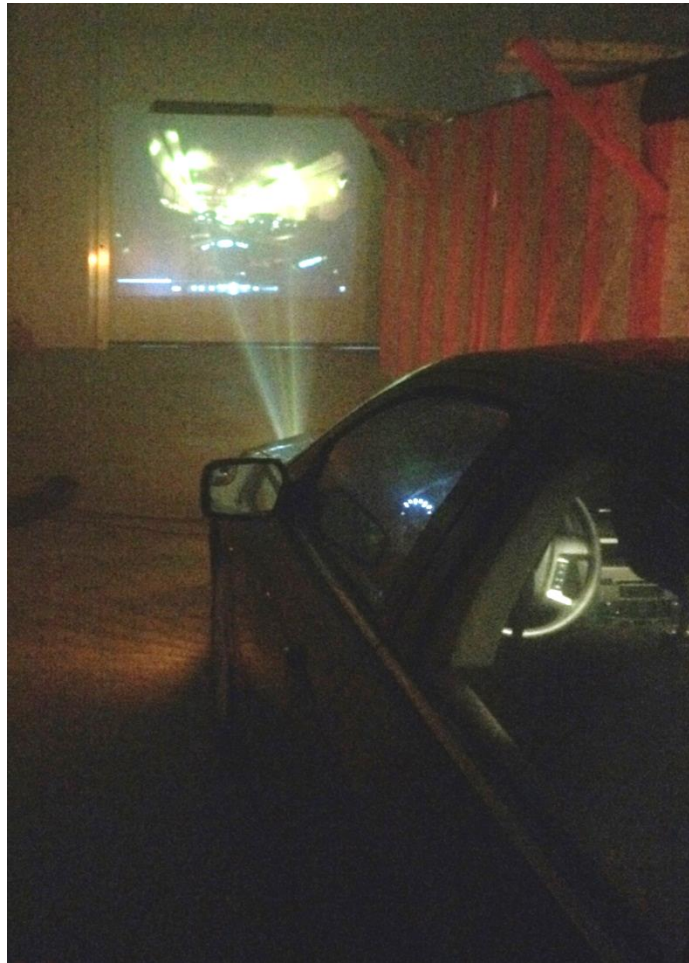


Figure 5. Tunnel simulation, Stage 1: video clip viewed from vehicle.

As the clip ended and the ambient sounds began, the experimental groups were provided information as follows:

- Group 1 participants were given no additional information beyond the ambient visual and audible cues from the video.
- Group 2 participants saw an overhead DMS displaying the message “FIRE IN TUNNEL—WALK TO EXITS.”
- Group 3 participants heard the following recorded audio message (via an MP3 player and portable speaker inside the vehicle): “Attention—there is a vehicle fire in the tunnel. Turn

off your engine and leave your keys in the vehicle so that it can be moved by emergency personnel. Leave your vehicle and walk quickly to emergency exits.”

Participant comments during the scenario were recorded. Following the video clip and any provided messages (DMS or audio), the researcher also prompted participants, as appropriate, with the following questions:

- “Given what you have observed so far, what would be your response at this point?”
- “What additional information would you look for?”

The researcher recorded all verbal responses to the questions, as well as any other participant actions in response to the simulated scenario. All participants, regardless of their experimental group and/or response to Stage 1, proceeded to Stage 2.







Stage 2: Sign/Marking Comprehension and Visibility

In Stage 2, participants viewed a selection of exit signs, pathway markings, and exit door markings and beacons. A total of six sign formats were tested:

- A running man symbol with no text (ISO 7010 version of the symbol). This sign was the first viewed by every participant and was shown only as an internally illuminated sign.
- A running man symbol plus the word “EXIT.” Every participant saw this format twice, once as an internally illuminated sign and once as a photoluminescent sign.
- A running man symbol plus “EXIT” text, a directional arrow, and numerals identifying a distance in feet. Every participant saw this format twice. The internally illuminated version of the sign included a distance of 168 feet, and the photoluminescent version of the sign included a distance of 154 feet. These distance numbers were chosen deliberately to make participants less able to guess at a number before they could actually read it; in actual practice, it would be more typical to position signs at more predictable distances such as 150 feet or 175 feet.
- A text-only EXIT sign. Every participant saw two versions of this sign. The internally illuminated version of the sign also included chevron-type arrows on either side of the text, pointing right and left. The photoluminescent version of the sign did not include arrows.
- An emergency telephone symbol-only sign. Each participant saw this sign once; the sign was photoluminescent.
- A symbol-only sign designating an emergency refuge area for persons with disabilities. Each participant saw this sign once; the sign was photoluminescent.

Each participant also viewed a set of photoluminescent path markers. These included no text or graphics and were a non-electronic version of the LED path markers that were also tested during Stage 2. Table 5 summarizes the emergency exit signs and other devices that were tested during Stage 2.

Table 5. Signs, Markings, and Beacons Tested in Tunnel Simulation, Stage 2.

Comprehension Questions and Visibility Distances		a. LED Version	b. PL Version
 1. Running man (RM) symbol		X	
 2. Running man with EXIT text (exit door version)		X	X
 3. Refuge area sign			X
 4. Emergency telephone sign			X
 5. EXIT text-only signs		X	X
 6. Running man + EXIT text + arrow + distance		X	X
Visibility Distance Only		a. LED Version	b. PL Version
7. Pathway markers			X
Exit Door Markers—Forced-Choice Preference/Confidence Pairs			
8a. Flashing green	8b. Steady-state green	X	
9a. Flashing green	9b. Flashing green + verbal audio beacon	X	
10a. Flashing green	10b. Flashing green (traveling)	X	
11a. Flashing green (traveling)	11b. Flashing green + verbal beacon	X	

The signs were shown in three different sign orders, with approximately one-third of participants assigned to each of the three orders. Varying the orders in which the signs were

presented served two purposes—to minimize the impact of learning effects on comprehension results and to ensure that the same signs were not always seen in thicker smoke (present at the beginning of each participant’s test) or thinner smoke (present toward the end of each participant’s test). The exception was the symbol-only running man sign, which was the first sign that every participant saw; this was to better test comprehension of the running man symbol (before participants saw the symbol in combination with the “EXIT” text. The sign orders are shown in Table 6.

Table 6. Viewing Orders of the Test Signs during Stage 2 of the Tunnel Simulation.

Sign Order 1	Sign Order 2	Sign Order 3
RM symbol	RM symbol	RM symbol
EXIT + arrows	RM + EXIT (LED)	Emergency phone
Emergency refuge	Markers (PL)	RM + EXIT + arrow + 154 ft
RM + EXIT (PL)	RM + EXIT + arrow + 168 ft	EXIT
Emergency phone	EXIT + arrows	RM + EXIT (LED)
RM + EXIT + arrow + 154 ft	Emergency refuge	Markers (PL)
EXIT	RM + EXIT (PL)	RM + EXIT + arrow + 168 ft
RM + EXIT (LED)	Emergency phone	EXIT + arrows
Markers (PL)	RM + EXIT + arrow + 154 ft	Emergency refuge
RM + EXIT + arrow + 168 ft	EXIT	RM + EXIT (PL)

Ambient lighting within the artificial tunnel was adjusted to approximately 10 lux (measured in smoke-free conditions at floor level) to approximate typical nighttime tunnel lighting levels, and the tunnel was then filled with artificial smoke, as shown in Figure 6. The density of the smoke was measured throughout each participant’s testing session, recorded each time the participant viewed a sign.



Figure 6. View of simulated tunnel, with partially dissipated smoke.

Procedure for Sign and Marking Comprehension/Visibility

Each participant viewed each sign treatment one at a time, using the 60-foot corridor. Distances were pre-marked on the floor, and the researcher assisted the participant in finding and staying close to this marked path.

All signs were viewed at a height of 1.4 meters (4.5 feet) from the floor/walkway level. Signs were mounted at a 10-degree angle from the side walls of the corridor, to approximate a likely viewing angle of a pedestrian standing in the vehicle lane (i.e., standing next to his/her vehicle) and viewing a sign mounted flat on a tunnel wall from about 12 meters (40 feet) away. This slight angling of the test signs toward the participant helped to compensate for the much more constricted viewing angles possible in the 6-foot-wide artificial tunnel (see Figure 7 and Figure 8).

Pathway markings were viewed at a height of 1 meter (3 feet) from the floor/walkway level, in accordance with CIE 193-2010 (see Figure 9).

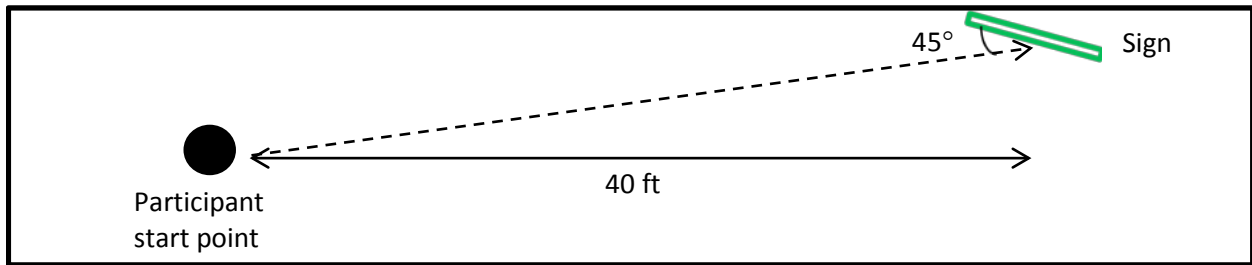


Figure 7. Viewing distance/angle for test signs.



Figure 8. Mounting brackets for test signs (shown without ambient smoke).



Figure 9. LED path lights in simulated tunnel.

This part of the simulation tested the following:

- **Detection distance:** For each of the sign and marking treatments, participants were asked to walk slowly forward from the start point marked in the corridor (a point at least 12 meters/40 feet away from the sign or marking) and to stop and tell the researcher when they could first see the sign or marking. The researcher recorded this distance, using distance markings on the floor of the corridor.
- **Legibility distance** (signs only): Participants were asked to continue walking slowly forward and to stop and tell the researcher when they could read the text and/or describe the symbol shown on the sign. The researcher recorded this distance.
- **Comprehension** (signs only): Participants were asked the meaning/message of the sign; in the case of exit signs that featured the word “exit,” participants were asked where they would expect to find the exit based on the sign. The researcher recorded the participants’ responses to these questions.

Procedure for Pathway/Exit Door Treatments

In place of actual exit doors, LED lights were used to mark pathways extending in both directions from the center of the corridor. The first four LED markers were placed at a height of 1 meter (3.2 feet) above the floor, spaced approximately 1.8 meters (6 feet) apart. The final LED marker in each direction was placed high on the wall close to each end of the corridor, in positions that would be at the top of standard-height doorways. In addition to the LEDs, an audio speaker was mounted at one end of the corridor close to the final LED doorway light. Participants viewed (and sometimes heard) each pair of pathway/door treatments from the center

point of the corridor; the researcher then asked, “Which direction would you be more confident about turning to find an exit?” and recorded the participants’ answers, along with the participants’ reasons for choosing as they did.

Exit Survey

Besides the sign comprehension questions that were asked in the simulated tunnel environment, participants answered questions about some additional symbol and color combinations in a brief exit survey conducted after they finished Stage 2. Pictures of the signs and symbols were presented to each participant on a laptop computer, and the researcher recorded the participant’s verbal responses.

RESULTS

Stage 1: Response to Emergency Situation and Messages

Information was collected for 63 participants in Stage 1. Only one participant physically left the vehicle in response to the simulation in Stage 1 (after hearing the audio message instructing drivers to leave vehicles). The rest of the participants responded only verbally regarding their response to the situation and the information presented. The comments offered by participants during and immediately following the simulated drive, as well as their responses to the questions, were used to categorize their probable reactions to the emergency situation as “more likely to stay in the vehicle” or “more likely to leave the vehicle.” Table 7 summarizes these two categories of responses across the three information conditions (ambient cues only, DMS message, audio message).

Table 7. Summary of Participant Responses to Tunnel Simulation, Stage 1.

Response	Ambient Cues Only	DMS Message	Audio Message	Total
Stay in the vehicle	16 (80%)	4 (19%)	6 (27%)	28
Leave the vehicle	4 (20%)	17 (81%)	16 (73%)	35
<i>Total</i>	<i>20</i>	<i>21</i>	<i>22</i>	<i>63</i>

Chi-square analysis of responses indicated that participants who received the DMS message were significantly more likely to indicate an intention to leave the vehicle versus participants who received ambient cues only: Chi-square critical value = 15.1; $p(X^2 > CV = 0.0001)$. Similarly, participants who received the audio message were significantly more likely to indicate an intention to leave the vehicle versus those who received ambient cues only: Chi-square critical value = 11.6; $p(X^2 > CV = 0.0007)$.

There was no significant difference in expressed intentions between the participants who heard the audio message versus those who saw the DMS message: Chi-square critical value = 0.43; $p(X^2 > CV = 0.51)$.

Staying or Leaving: Participant Comments

Participants who indicated that they would be more likely to stay in their vehicle tended to talk about needing more information, waiting to see what others would do, waiting to see if smoke or fire got closer to them, or simply feeling that remaining in the vehicle would be the

safest course of action. Example comments from participants who indicated that they would be more likely to stay in the vehicle, at least until something else caused them to decide to leave, are listed below.

Comments from participants who received no warning message included:

- *I would stay in my car, maybe roll down my window to see if other people were getting out, but I definitely wouldn't get out first. Actually, I probably would just be wishing I had cell phone reception.*
- *I'd probably stay in my car, to be honest. I might eventually leave, would run in the opposite direction from the smoke.*
- *Can't get out because there are cars in front and back of me. If I left my vehicle it would be blocking the tunnel, or at least the lane. I would just sit and see if it was going to clear up and if the traffic would start moving again.*
- *I'd probably stay in the car unless things started getting hot. I might open the door to see if the smoke was all the way to the ground; if not, I might crawl out. If the whole tunnel is full of smoke, you're going to have to make a decision pretty fast.*
- *I'd stay in my car and see what might happen; if I had my phone I would call 911 and see if they could tell me what was happening. I might get out and talk to the person behind me to see if they know what's going on, but then might get back in my car—I feel like that might be safer.*
- *I would stop or slow down and see what is ahead and what options I have, either getting around it or getting out of it. Right now I think the only option I have is to stay with it, moving slowly or stopping as needed, and just work my way through it.*

Comments from participants who received a DMS or audio warning but still indicated they would be more likely to stay in the vehicle included the following:

- *I'm not going to get out without knowing what's out there. I'll wait for more information like what we heard on the radio. I would open it up to look, but I would stay in the car until I heard more about what to do. I'd want to wait until other cars were stopped, see what people in other cars were doing.*
- *Probably stay in my car and see what other people do.*
- *I'd be sitting in the car thinking "where the hell is an exit?" Because I hadn't seen any exit signs along the way that I'm aware of.*

Participants who indicated that they would be likely to leave their vehicle seemed either to recognize that smoke or fire in a tunnel presented an immediate hazard or to trust an official-sounding instruction to leave. Example comments are listed below.

Comments from participants who received no warning message but indicated they would leave their vehicle included:

- *I'd get out of my car and try to analyze by the available light how to exit and get out; the first place I would look is up, to see if there's any potential on those walls. I'm a brainstormer, so I would get with some other drivers and start strategizing a way out of there. Forget the car; I would take my purse, I'd be trying to call 911. I'd be extremely worried*

for elderly and handicapped people, and would organize a search for anyone needing help inside the other vehicles. I'd be taking action.

- *If it's smoke, I would think something is in danger of exploding and I would do my best to get away from it, if possible. If there was no way around in my car, I would probably get out to see, and run away if it looks dangerous. My life is more important than my car!*

Comments from participants who received a DMS or audio warning and indicated they would leave their vehicle were:

- *[DMS message] It says "walk to exit." I guess I'd walk to the exit. I'd head toward that sign. If I didn't have anything to carry with me, or any family to worry about, I'd probably make it.*
- *[DMS message] I remember passing the exit just several car lengths back, so I'm going to exit the car, go back and take that exit. It was kind of hard to see; I didn't see a lit exit sign. That would help, kind of like an exit sign in a building.*
- *[DMS message] I noticed when I was driving that there seems to be a railing to the left, so there's probably a walkway there. Assuming my cell phone was charged, I would turn it on and turn on the flashlight. Get out of the car, since that's what I'm being told to do, take my keys with me. If I knew the tunnel and had a good feeling for how long it was, I'd know which way to walk. If I didn't know the tunnel, I would probably walk back the way I came.*
- *[Audio message] If I hear someone telling me to get out of the car, I'm getting out of the car. I can guarantee you that's exactly what I'd do. I'd leave the key in the car. I'd probably try to grab my iPad, personal items, maybe grab some water if I had it in the car. And when I got out, I'd expect to see other people getting out too.*
- *[Audio message] I would probably listen to what he said and get out. Because that would be the emergency folks telling us what to do.*
- *[Audio message] I guess I'd get everyone out of the car and leave. I'm always attached to my keys, so leaving the keys in the car might be a challenge. I would assume that is what I'd do. If you see a fire in a tunnel, I'm not sure I would know what to do, so having a voice tell me what to do would be helpful, along with seeing other people getting out and leaving.*

Additional Information Needs

Participant responses regarding additional information they would want to have most often fell into one of the following categories:

- Location of emergency exits.
- Pathway or other emergency lighting.
- Cause of the incident.
- Seriousness of the incident/situation.
- Instructions about what to do.

Table 8 summarizes the number of requests that were made by participants for each type of information under each of the three conditions. These total more than the number of participants since many participants listed several types of information that they would want.

Table 8. Tunnel Simulation, Stage 1: Additional Information Wanted.

Additional Information Wanted	Frequency of Request for Each Participant Group		
	Ambient Cues Only (20 participants)	Audio Message (21 participants)	DMS Message (22 participants)
Location of exits	4	15	17
Lights/path	7	8	12
Instructions about next actions	11	4	3
Cause of incident	12	2	3
Seriousness of incident	11	1	3
Other	0	7	1
None	0	2	1

As can be seen in the table, there was a difference in the information needs most frequently identified by participants who received only ambient cues about the emergency, versus those identified by participants who received one of the two messages. Participants who received only ambient cues were more likely to ask for instructions about what to do and about the cause of the incident and the seriousness of the incident—information that had already been provided to the other groups of participants. Participants who received either of the two messages were more likely to ask about exit locations and how to find them.

Other information needs that were mentioned by some participants included instructions to drivers to stop and/or watch for pedestrians, information about where drivers should stop (e.g., within their current lane or on a specified side of the tunnel), information about who/what entity was making the announcements (e.g., tunnel operator, emergency services), whether there would be additional announcements that people should be listening for, what would happen to abandoned vehicles, and where people should gather once they were out of the tunnel.




Stage 2: Sign Comprehension

Each time a participant indicated that he or she could see/read the words and/or symbols on a sign, the researcher asked, “What is on the sign?” Once the participant had described the symbols and/or read the text on the sign, the researcher asked the participant about the meaning of the sign.

Symbol-Only Signs

For signs that displayed symbols only (no text), the researcher then asked, “What do you think the sign is telling you?” Participants’ verbal responses to these questions were recorded and later scored according to how closely each participant’s interpretation of each sign matched the intended meaning of the sign. The scores for symbol-only signs are summarized in Table 9 as “correct,” “partially or near correct,” and “incorrect or don’t know.” Descriptions of these scores for each sign type are described in the subsections below.

Table 9. Comprehension Scores for Symbol-Only Signs.

Sign		Correct Definition	Partially or Near Correct	Incorrect or Don't Know
Running man symbol		29 (48%)	23 (38%)	9 (15%)
Refuge point		5 (8%)	46 (75%)	10 (16%)
Emergency phone		53 (87%)	7 (11%)	1 (2%)

Running Man Symbol. The running man symbol was the first sign each participant saw; this order was intended to gauge how well the symbol was comprehended as a stand-alone information element. Most participants identified the symbol as a “running person,” “running man,” “someone running,” or “pedestrian.” When asked what the sign meant, 29 participants (48 percent) said that it indicated an exit (scored as “correct” in Table 9); another 23 (38 percent) said that it indicated a walkway or path that they would follow (scored as “partially/near correct”).

The nine participants whose responses were scored as “incorrect” thought the sign was a pedestrian crossing sign, to warn drivers that someone may be crossing the roadway in front of them.

Emergency Phone Symbol. This sign was included in the comprehension testing primarily to reduce the expectation that every sign would have something to do with an exit from the tunnel. Sixty out of 61 participants (98 percent) identified the phone and flame symbols on the sign; 53 out of 61 (87 percent) specifically stated that the phone was an “emergency” phone or a “phone to report a fire.” Seven participants (11 percent) indicated that the sign indicated a phone, but not necessarily for emergencies; one of these stated that it might be a phone that is fire protected. One participant stated that he/she had “no idea” what the paired symbols might mean.






Refuge Point. This sign, which like the emergency telephone sign was included to indicate something other than an exit from the tunnel, was the least-recognized symbol among the participants. While all participants correctly identified the wheelchair symbol as indicating something pertaining to people with disabilities, only five (8 percent) stated that the sign identified a safe/refuge area. Ten participants guessed that the sign indicated something (but could not guess what) for a disabled person, or that it was warning drivers to watch for people with disabilities close to the road. The remaining 46 participants guessed that the sign marked an accessible exit door or ramp, or a stored wheelchair that could be used to transport a disabled person.

Signs Including “EXIT” Text

For signs that included the text “EXIT,” the researcher asked the participants, “Where would you expect to find the exit, based on this sign?” Participant responses were scored as “correct” if their expectation for the sign location matched the customary use of the sign (i.e., a text EXIT sign or a running man sign with no directional arrow would be used on or above an exit door; signs with directional arrows would be used to indicate that an exit would be in the direction of the arrow or arrows). Table 10 summarizes the comprehension scores for the signs that included EXIT text as part of the legend.

It should be emphasized that the comprehension scores in Table 10 should be not considered as having identical meanings to the comprehension scores for the symbol-only signs shown in Table 9; it can be assumed that all participants recognized the signs containing EXIT text as representing exits. The correctness of participant responses for the signs containing text refers only to where participants expected to find exits, based on a given sign.

Table 10. Comprehension Scores for Signs with Text.

Sign	Correct Exit Location	Partially or Near Correct Location	Incorrect or Don’t Know	
Running man + EXIT text (1 st viewing)		16 (26%)	45 (74%)	0 (0%)
Running man + EXIT text (2 nd viewing)		11 (18%)	50 (82%)	0 (0%)
Running man + EXIT + distance + arrow (1 st viewing)*		60 (98%)	1 (2%)	0 (0%)
Running man + EXIT + distance + arrow (2 nd viewing)*		59 (97%)	1 (2%)	1 (2%)
EXIT text + arrows		46 (75%)	2 (3%)	13 (21%)
EXIT text only		51 (84%)	7 (11%)	3 (5%)

*Participants in Groups B and F saw the “154 ft” sign first; participants in Groups A, C, D, and E saw the “168 ft” sign first.

Running Man with EXIT Text. Participants saw this sign format twice, once as an LED-illuminated sign and once as a photoluminescent sign. All participants identified this as an exit sign; most (74 percent on first viewing, 82 percent on second viewing) thought that it indicated an exit nearby but past the sign in the direction that the running man was facing (scored as partially or near correct in Table 10). A smaller percentage (26 percent on first viewing, 18 percent on second viewing) identified the sign as being an exit door sign; this was scored as “correct” in Table 10.

Running Man with EXIT Text, Arrow, and Distance. Participants saw one LED-illuminated sign showing an exit 168 feet to the right, and one photoluminescent sign showing an exit 154 feet to the left; Participant Groups B and F saw the 154 feet sign first, while the other groups saw the 168 feet sign first. Nearly all participants comprehended both of these signs correctly, stating that the exit was in the direction that the arrow was pointing, at the stated distance away. Some participants commented that while they were uncertain of how far 168 feet or 154 feet would be, the sign nonetheless provided them with the information that the exit was some distance away, not in the immediate area. A small number of participants stated the distance and then translated that distance into an approximate number of paces that would get them to the exit.

One partially correct response for this sign was a misreading of the number as 15.4 feet instead of 154 feet; the other was a statement that the exit was “to the left of that sign” (the direction of the arrow) without specifying a distance. The only incorrect interpretation of this sign was from one participant who thought that it could mean “exit here, then go 168 feet in the direction of the arrow.”

EXIT Text Signs with Chevron Arrows (Two Directions). Participants saw two versions of an EXIT text-only sign: an LED internally illuminated sign that included two chevron arrows (indicating exits in either direction) and a photoluminescent EXIT sign without arrows. The EXIT sign with the bi-directional arrows was recognized by all participants as indicating one or more exits, but participants’ expected locations of those exits were not as consistent. The correct answer, that the two arrows indicated exits in both directions, was stated by 46 of the 61 participants (75 percent). Two participants (3 percent) stated that the exit was next to the sign, implying an exit in one direction rather than two. The remaining 13 participants (21 percent) assumed that the exit would be directly below the sign; some of these, from their comments, seemed not to recognize the chevron arrows as representing directions (one participant said specifically that they looked like brackets).

EXIT Text Signs (No Arrows). All participants recognized the sign as identifying an exit, and 51 out of 61 (84 percent) expected that the sign would be hanging on or directly above the exit door. Another seven (11 percent) expected to find the exit door in close proximity to the sign. Three participants (5 percent) stated that they were uncertain where an exit would be in relation to the sign’s location.

Stage 2: Sign Visibility

Results for the sign detection and legibility distances are included in Chapter 5, along with the luminance measurements for each sign.

Stage 2: Path Marking Preferences

Four formats of pathway/exit door beacons were tested. All of these formats included a series of green LED lights spaced approximately 1.2 meters (4 feet) apart along the wall at a height of 1 meter (3.2 feet). The final LED light at either end of the artificial tunnel structure was positioned high on the wall to simulate a light just above a doorway. The four formats included the following:

- Steady-state LEDs (no flashing).
- Unison flash, in which all of the LEDs along the path flashed on and off at the same time.

- Traveling flash, in which the LED lights flashed individually in a repeated sequence from left to right (from the perspective of the viewer) and thus appeared to travel to the right.
- Unison-flash LEDs plus an audio beacon at the door location.

As described in the procedures section, these four options were presented to participants in pairs, as shown in Table 11, with one option in each pair to the left of the participant and the other option to the right of the participant. The participant was then asked, “Which direction would you be more confident about going to find an exit (left or right)?” A follow-up question asked for the participant’s reason for his or her preference.

Table 11. Path/Door Marking Comparisons.

Comparison	Most Frequently Preferred	Number Preferring (out of 61)	Percent Preferring
Unison flash vs. steady state	Unison flash	37	61%
Unison flash vs. unison flash + audio	Unison flash + audio	56	92%
Unison flash vs. traveling flash	Traveling flash	49	80%
Unison flash + audio vs. traveling flash	Unison flash + audio	44	72%

Unison Flash versus Steady State

Participants viewed a series of steady-state (continuously lit) LED path markers to the right and a series of LED path markers to the left that flashed in unison. Sixty-one percent of participants preferred the unison-flash markers to the steady state. Comments from participants who preferred the unison-flash markers included the following:

- *The blinking draws attention.*
- *It indicates “emergency” and “attention.”*
- *The flashing says, “Move!”*
- *It seems like it’s active, that it’s trying to point out something.*
- *Steady lights are just lighting; the flashing lights are telling me to do something.*
- *You can tell it’s not just normal lighting; since it draws your attention, it must matter more.*

Comments from participants who preferred the steady-state markers included the following:

- *Sometimes blinking means “hazardous”; the solid [steady-state] markers look like an airplane exit path.*
- *The flashing almost seems like something’s wrong, while the steady lights are reassuring.*
- *I don’t particularly like strobe lights because they’re a little disorienting. Maybe a slower flash rate would be better.*

- *The flashing almost looks like “watch out, there’s a problem.”*
- *The steady lights are not as disorienting and provide easier depth perception in a smoky environment.*

Unison Flash versus Unison Flash plus Audio

In this comparison, both the left and the right series of LED path markers flashed in unison; in addition, an audio beacon to the left of the participant (approximately 8.5 meters or 28 feet away) repeated the phrase “exit here,” alternating between English and Spanish. Ninety-two percent of participants preferred the addition of the audio message to the path markers alone. Comments from participants who preferred the addition of the audio message included the following:

- *I’d follow the sound.*
- *The voice is telling me to go that way.*
- *That’s where the sound is coming from. In this case, the flashing lights call attention to the voice and the path.*

There were no participants who stated that they preferred the flashing lights without the audio beacon, but some had no preference between the two pathway directions. Comments from these participants included the following:

- *I wouldn’t trust the direction of the voice; it’s inadequate as a directional guide.*
- *I can’t tell where the voice is coming from.*
- *I’d change the message to “follow my voice and exit here.”*

Unison Flash versus Traveling Flash

Participants viewed a series of LED path markers to the left that flashed in unison, and a series to the right that flashed individually in a repeating sequence that began with the marker closest to the participant and traveled down the wall to the right. Eighty percent of participants preferred the traveling flash to the unison flash. Comments from participants who preferred the traveling flash option included the following:

- *I like the progression of the lights telling me the direction to go.*
- *It looks like an arrow.*
- *I see which direction it wants me to follow.*
- *It’s a slower blink than the [unison flash]; it doesn’t mess with my eyes as much. Besides, the lights imply “that way,” like runway lights.*

Comments from participants who preferred the unison flash included the following:

- *The [unison flash] is more prominent.*
- *It seems to be blinking faster than the other direction.*
- *Both are good; [unison flash] is drawing me [toward it] more.*

Unison Flash plus Audio versus Traveling Flash

The unison-flash LED lights plus the “exit here” audio beacon were presented to the participants’ left, while the traveling flash LED path (with no audio) was presented to the right. Seventy-two percent of participants preferred the unison flash plus audio to the traveling flash, but several of these commented that a combination of the two strategies would be ideal. Comments from participants who preferred the unison flash plus audio option included the following:

- *Easier to go toward the voice, especially if you’re disoriented.*
- *The voice outweighs the [traveling] lights.*
- *The voice gives me immediate confidence to go that way.*
- *The voice is more prominent, but I would recommend using both.*
- *The voice is good, but [traveling] lights would also be powerful; the voice could be echoing more in a tunnel.*

Comments from participants who preferred the traveling flash option included the following:

- *“Exit here” may not mean anything if I’m disoriented; also [the traveling light path] is a little calmer.*
- *The arrow effect is good.*
- *In a tunnel, it might be hard to tell where the voice is coming from.*

Exit Survey Responses

The first question in the exit survey asked, “Does the direction the running figure is facing always indicate the direction of the exit?” (see Figure 10). Of the 63 participants, 58 (92 percent) answered “yes” to this question, which is consistent with how most participants interpreted the directionality of the running man signs during Stage 2.

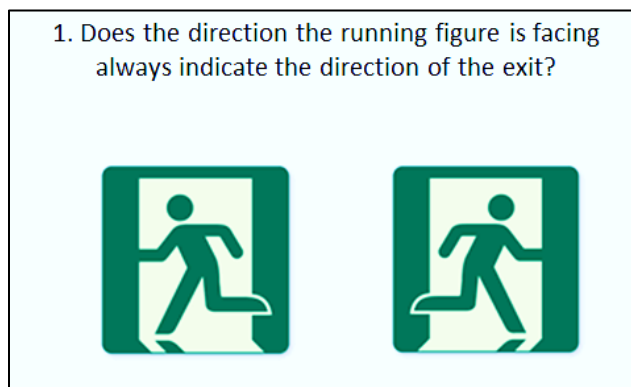


Figure 10. Exit survey, question 1.

Question 2 asked whether a running man symbol on a sign meant the same thing to participants as the symbol accompanied by the word “EXIT” (see Figure 11). Fifty participants (79 percent) answered that the two signs meant the same; of these, 48 nevertheless preferred the version that included the “EXIT” text, feeling it provided more clarity.

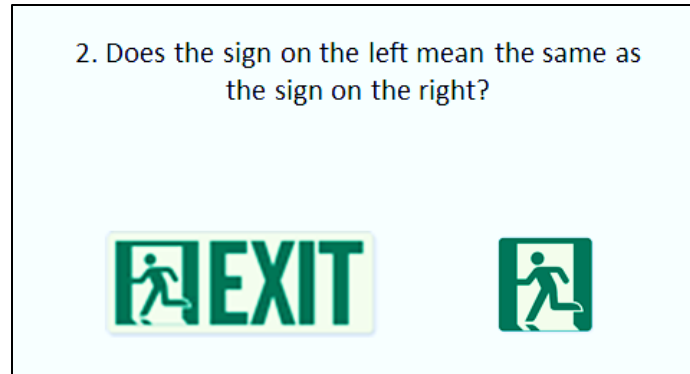


Figure 11. Exit survey, question 2.

Question 3 asked whether the running man symbol meant the same to participants as the traditional EXIT text sign (see Figure 12). Responses were mixed, with 30 participants (48 percent) answering that the two signs had the same meaning and 33 participants (52 percent) answering that the signs had different meanings. Of the 30 participants who felt that the two signs had equivalent meanings, 22 preferred the text EXIT sign, most often because they felt it was clearer and more familiar. Participants who answered that the two signs had different meanings tended to interpret the running man symbol as indicating an upcoming exit in the direction that the running man was facing, versus assuming that the text EXIT sign would be used at the location of the exit itself.

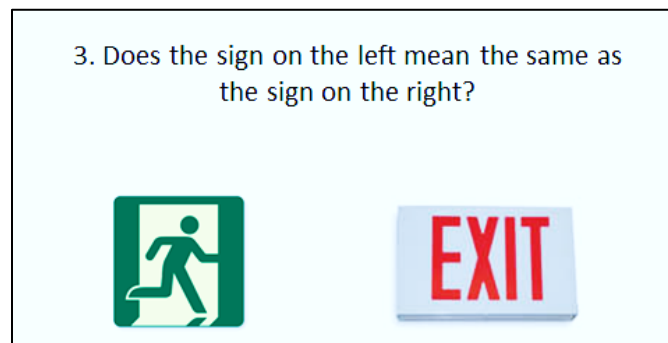


Figure 12. Exit survey, question 3.

Question 4 asked whether a red EXIT text sign meant the same to participants as a green text sign (see Figure 13). Fifty-seven participants (90 percent) answered that the two sign colors had the same meaning; of these, 31 preferred red and 16 preferred green. Participant comments about sign colors included the following:

- *Green means that you can exit this direction at any time. Red would mean it's an emergency exit only.*
- *In the tunnel, I could see green easier than red.*
- *I'm more accustomed to a red exit sign.*

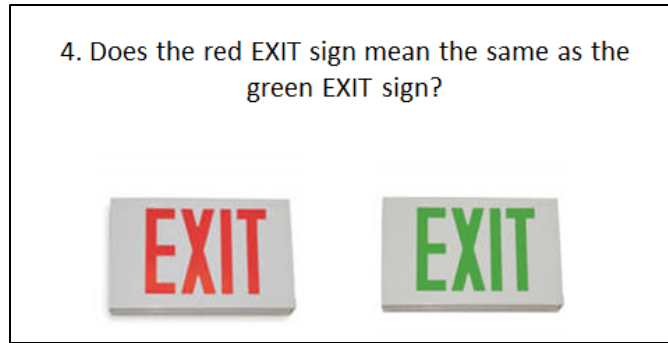


Figure 13. Exit survey, question 4.

Question 5 asked if a running man symbol alone meant the same thing to participants as a running man sign paired with a directional arrow (see Figure 14). Fifty participants (79 percent) answered that the addition of the arrow did not change the meaning of the sign (in actuality, the running man symbol by itself is generally used for an exit door, while the addition of an arrow indicates that the exit is in the direction of the arrow). This again underscores the prevailing view among the study participants that the running man symbol by itself indicated direction.

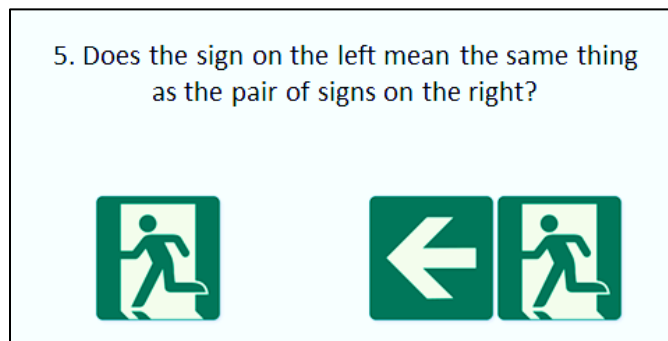


Figure 14. Exit survey, question 5.

Questions 6 and 7 paired a running man symbol with arrows pointing directly up and down, respectively, and asked what the symbol combinations would mean to participants (see Figure 15).

Twenty-two participants (35 percent) selected one of the two provided answers: that the down arrow likely meant “you are at the exit,” with some of these stipulating that they would expect this combination to be positioned above a doorway. Seven participants (11 percent) selected the answer “you need to keep going in your current direction for the exit.” The other 33 participants (52 percent) provided other definitions for this symbol combination, with most answering that the arrow would indicate a staircase, elevator, or downward slope.

The up arrow was also identified by the largest number of participants (26, or 41 percent) as indicating an upward staircase, ramp, or elevator. Twenty participants (32 percent) selected the provided answer “you need to keep going for the exit,” and eight selected the answer “you are at the exit.”

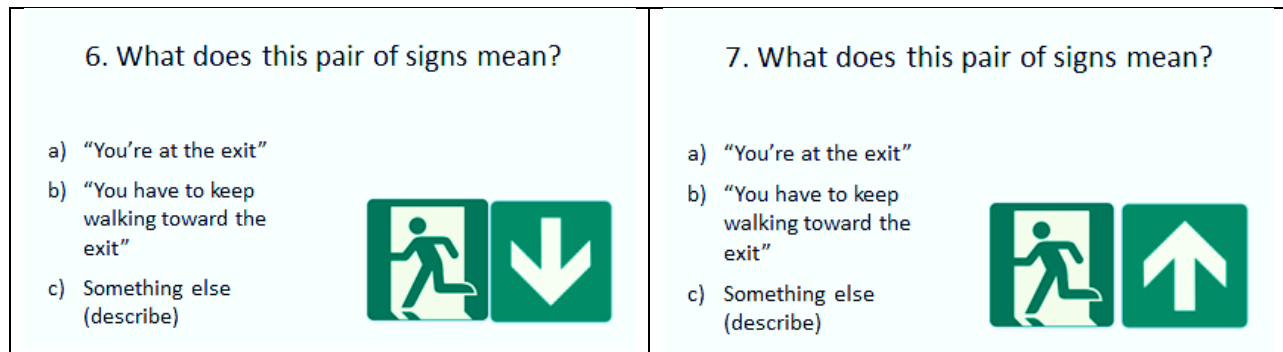


Figure 15. Exit survey, questions 6 and 7.

Questions 8 and 9 similarly paired a running man symbol with different directional arrows (an arrow pointing directly right versus an arrow pointing right but angled either up or down, as shown in Figure 16.) Most participants (57, or 90 percent, for the downward-angled arrow; 59, or 94 percent for the upward-angled arrow) believed that the arrow pointing directly right indicated that an exit would be on the same level as the pedestrian, while an angled arrow indicated that the pedestrian would have to go up or down, most likely via a staircase. A couple of participants thought the angled arrows could indicate an exit at the same vertical level, but in a diagonal direction or around a corner from the location of the sign.

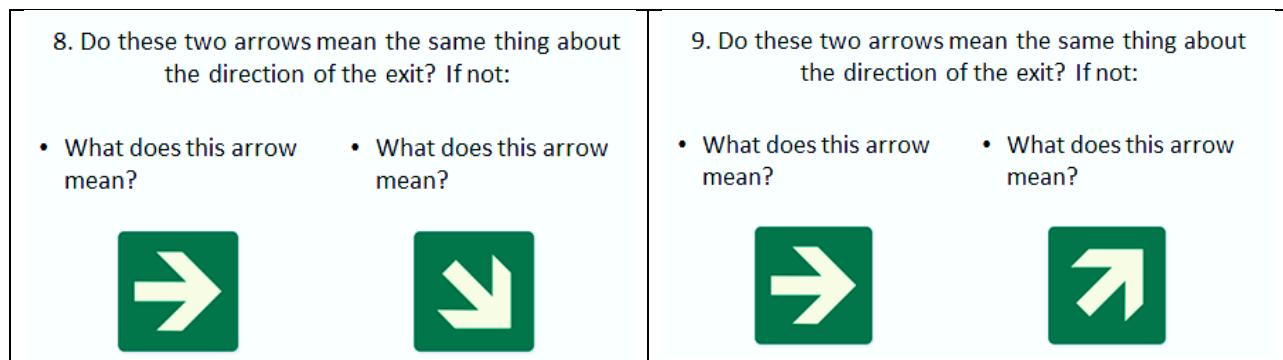


Figure 16. Exit survey, questions 8 and 9.

Question 10 asked participants if small chevron arrows and tailed arrows meant the same thing when used with exit signs (see Figure 17). Fifty-seven participants (90 percent) answered that the two arrows had the same meaning, though 47 of these preferred the tailed arrow to the chevron arrow for visibility and/or clarity. Comments from the small number of participants who indicated that the two arrows had two different meanings included the following:

- *The chevron arrow means that the exit is underneath the sign and to the right. The tailed arrow means that exit is coming up to the right, but you need to keep walking.*
- *The chevron doesn't look like an arrow, especially if it's on both sides. Maybe three chevrons in a row would look more like a direction.*

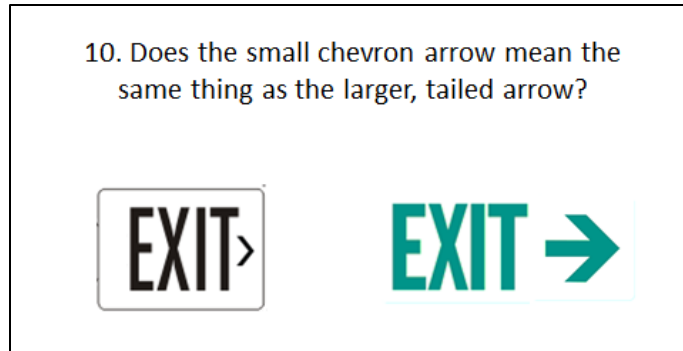


Figure 17. Exit survey, question 10.

Question 11 asked participants if a running man exit sign that included a distance along with a directional arrow meant the same as the directional sign without a distance (see Figure 18). Responses were mixed, with 37 participants (59 percent) answering that the two formats meant the same thing and 26 participants (41 percent) answering that the two signs provided different messages. Participants who indicated that the two signs provided different messages most frequently assumed that the sign without a specific distance included should indicate an exit that is only a short distance away. Participant comments, regardless of the answer selected, were very similar—most preferred the sign that included the distance, feeling that it provided clearer and more complete information to pedestrians.

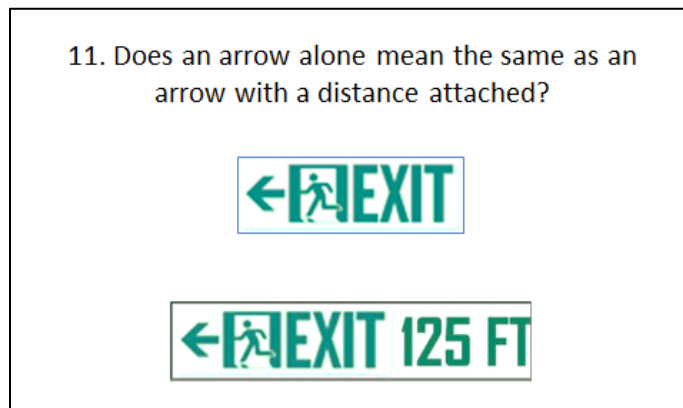


Figure 18. Exit survey, question 11.

TUNNEL SIMULATION CONCLUSIONS

Stage 1 of the tunnel simulation indicated that providing an evacuation message to drivers during an emergency situation increases the likelihood that they will leave their vehicle. The message mode (sign or audio) did not seem to greatly influence this result, as long as drivers received the information in one form or another. As seen in the focus group results, the most important message elements seemed to be an explanation of the situation and direct instruction; the drivers who did not receive a message in Stage 1 were most likely to ask for these pieces of information. Once drivers indicated their decision to leave the vehicle, their most frequent questions were about how to find and identify exits. One caveat that should be noted regarding the audio message is that participants heard this message via a small speaker inside the vehicle, not from a loudspeaker outside the vehicle. The sound quality and therefore the intelligibility of

the audio message would be greatly reduced if it were broadcast over a loudspeaker inside a tunnel.

Exit Sign Comprehension

In Stage 2, participants had little or no trouble comprehending most of the exit signs. The stand-alone running man symbol that was presented first was identified correctly by 48 percent of participants as an exit sign, while another 38 percent assumed that the sign indicated a direction or path for them to follow. Once the running man symbol was paired with the word EXIT, the most common misconception by participants had to do with where they would expect to find the exit door in relation to the sign.

Most participants thought that the running man sign (with or without the word EXIT) indicated a direction, even without a supplemental arrow. Because of this inferred directionality, the most frequent assumption among participants was that the running man symbol indicated an exit that was to the side of the sign or farther away in the direction that the running figure was facing. It should be noted, however, that participants saw all signs in the context of a wall-mounted frame and so did not have the added context of a visible doorway.

Conversely, the only notable misconception about the text-only EXIT sign was related to the version of the sign that included chevron arrows in two directions; a small number of participants did not recognize the directionality of this sign and assumed that it must be above the exit door itself. The confusion among those participants seemed to lie with recognition of the chevrons as directional arrows, and the familiarity of seeing text EXIT signs above exit doors.

When the running man sign was paired with a (tailed) directional arrow and a distance, comprehension was perfect among nearly all participants. A directional arrow without a distance included (tested with a text EXIT sign in Stage 2 and with a running man sign in the exit survey) was generally understood to indicate that an exit would be found in the direction of the arrow, but most participants felt that specifying the distance to the exit provided clearer information. The assumption among many participants was that an arrow without a specified distance implied that the exit was nearby.

Tailed arrows were preferred by participants over chevron arrows for indicating a direction to an exit. Tailed arrows pointing directly left or right were clearly understood; arrows pointing or angled up or down required explanation.

Path Markings and Audio Beacons

Directional/traveling path markers leading to an exit door and an audio beacon at the door location were the most preferred options among those presented to participants; when these two measures were placed opposite each other, more participants ultimately preferred the audio beacon as a directional aid. However, it should be noted that the audio beacon was less than 30 feet away, and acoustics in the artificial tunnel are not the same as in an actual tunnel (and a few participants still had trouble determining the direction the sound was coming from). Audio beacons would therefore be effective only at short distances (and in locations where ambient noise levels would not be likely to mask the sound), while the effectiveness of directional path lighting would extend over longer distances.

Non-directional path markings were also considered valuable; participant preferences were mixed about flashing versus steady-state markers, with a slight majority preferring flashing markers.

CHAPTER 5. PHOTOMETRIC MEASUREMENT PROCEDURE AND RESULTS

The researchers took photometric measurements to quantify the visibility for each of the study treatments using two different methods. First, they monitored the opacity of the smoke throughout the study to quantify the available visibility during testing. A Wager 6500 smoke meter (Figure 19a) provided a continuous output of smoke opacity in the vicinity of the signs in the artificial tunnel. The percent opacity was recorded each time a participant viewed a sign. Zero percent opacity would equate to a clear tunnel with no smoke; 100 percent opacity would prevent any transmission of light.

Separately from participant testing, luminance measurements of test signs were conducted using a calibrated Remax/Radiant Imaging PM-1600 charge-coupled device (CCD) photometer (Figure 19b).

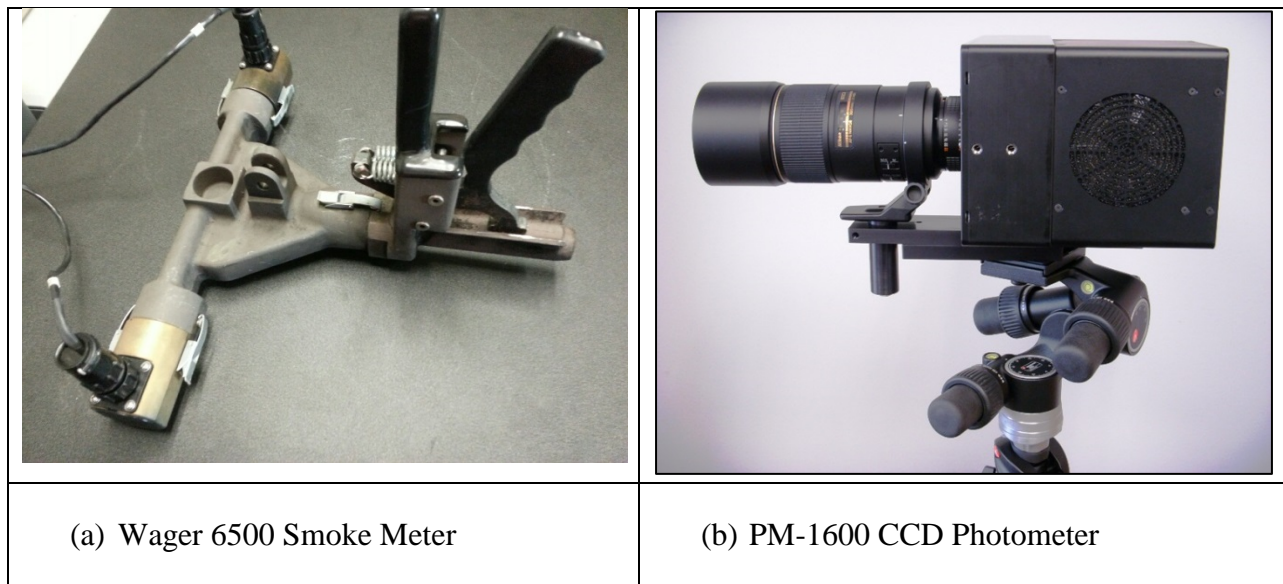







Figure 19. Equipment used to measure smoke opacity, sign luminance and contrast.

LUMINANCE MEASUREMENT RESULTS

Table 12 describes the signs that were measured with the photometer. These signs represented two different types of sign technologies (internally LED-illuminated and photoluminescent) as well as positive versus negative contrast. Positive contrast signs typically consist of a light-colored legend against a darker background. The positive contrast signs tested in this study were the two text-only EXIT signs, one with text that was internally illuminated by LEDs and the other with photoluminescent text, both against non-illuminated backgrounds. (The LED and PL versions of the directional arrows, seen as part of the running man exit distance signs, were also positive contrast.) Negative contrast signs have a darker legend against a light (or illuminated/photoluminescent) background. The running man symbols and accompanying EXIT and distance text are all positive contrast sign elements. All of the signs that participants viewed in the tunnel simulation represented variations of the two technologies and the two contrast types shown in Table 12.

Table 12. Signs Measured with Photometric Equipment.

	Sign	Comments
Running Man Exit Distance (LED)		Portions of the sign are covered by gray tunnel wall panels to provide background contrast
Sections of Running Man Exit Distance (PL)		Individual panels (EXIT, arrow, distance) are measured individually against a gray background
Text EXIT with Illuminated Letters (LED)		Sign background/casing is white but appears dark in low light levels when text is illuminated
Text EXIT with Glow Letters (PL)		Sign background is red but appears darker in low light
PL Marker		Photo shows PL marker (top) against gray background (bottom)

Each of these signs was measured under non-smoke and smoke conditions and under two ambient lighting conditions: with the emergency-level ambient lighting conditions used during the participant testing (set at approximately 10 lux) and with no ambient light. While luminance should not change with distance for most treatments under non-smoke conditions, it will under smoke conditions, so measurements were completed at multiple viewing distances and smoke opacity levels, as shown in Table 13. Measurements included the luminance levels of each treatment’s positive (brighter) and negative (darker) elements, as well as the luminance of the gray painted background around each sign (representing the tunnel wall). This allowed researchers to calculate the luminance contrast of the positive and negative elements within each sign, as well as the contrast between each sign and the tunnel wall.

Table 13. Luminance Measurements and Conditions.

Luminance Measurements	Overhead Lighting	Viewing Distance	Opacity
<ul style="list-style-type: none"> • Positive (brighter) element of sign • Negative (darker) element of sign • Gray background behind sign 	Yes	5 feet (1.5 meters)	0%
			12%
			23%
		10 feet (3 meters)	5%
			10%
		25 feet (7.6 meters)	4%
	No	5 feet (1.5 meters)	0%
			12%
			23%
		10 feet (3 meters)	5%
			10%
		25 feet (7.6 meters)	4%

Luminance and Contrast in Smoke

The photometric measurements quantified the effects of the artificial smoke on luminance and contrast levels of the test signs. As shown in Figure 20, the effective luminance of both LED and PL signs viewed from 10 feet (3 meters) away declined sharply at low levels of smoke opacity. The “EXIT” segment from the LED running man exit distance sign’s measured luminance of 335 cd/m² (97.8 fL) in clear conditions dropped to 74.1 cd/m² (21.6 fL) with a smoke opacity of only 5 percent; at 10 percent smoke opacity, the effective luminance of the sign was 29.8 cd/m² (8.7 fL). A viewing distance of 5 feet (1.5 meters) reduced the effects of smoke opacity somewhat (93.6 cd/m² or 27.3 fL at 12 percent smoke opacity, 34.2 cd/m² or 10 fL at 23 percent opacity), but the effects were still dramatic. The PL sign began at a much lower luminance level (12 cd/m² or 3.5 fL with no smoke) and declined to 5.9 cd/m² (1.7 fL) at 5 percent smoke opacity and 4.7 cd/m² (1.4 fL) at 10 percent smoke opacity (both at a 10-foot/3 meter viewing distance).

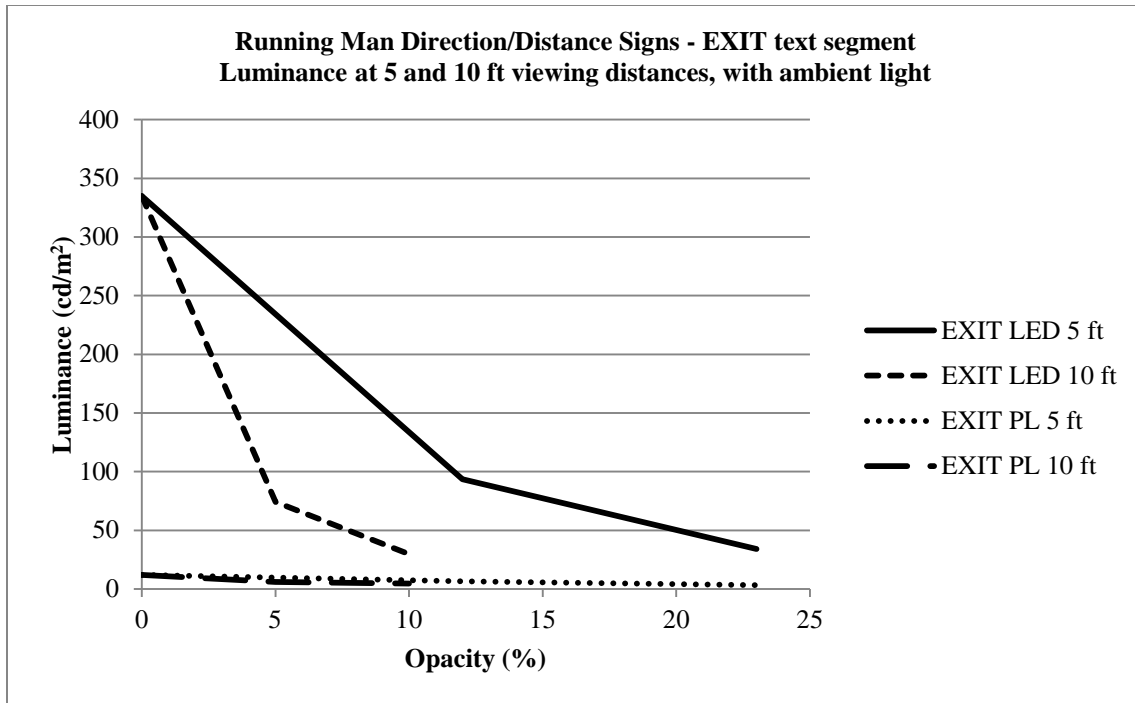


Figure 20. Luminance measurements of selected LED and PL negative contrast signs.

Besides the sharp drop in visible luminance from the test signs as smoke opacities increased, significant declines were seen in the contrasts between the signs and the tunnel wall and between the signs' positive and negative luminance areas. Figure 21 shows the contrast ratios of the LED and PL running man signs—specifically the contrast between the illuminated/glowing backgrounds of these signs with the gray tunnel wall panels under an ambient light level of approximately 10 lux. The luminance ratio of the LED sign backgrounds to the tunnel wall was approximately 72:1 in clear conditions; at a 10-foot viewing distance, this ratio dropped to 5:1 at 5 percent smoke opacity and less than 3:1 at 10 percent smoke opacity. The PL signs also declined in contrast with the wall background, from 9:1 with no smoke to 1.5:1 and then 1.1:1 at 5 percent and 10 percent smoke opacities, respectively.

When there was no ambient light, and therefore much less veiling luminance from light reflecting off smoke particles, contrast ratios between the signs and the tunnel walls improved. Figure 22 illustrates the contrast ratios at the same viewing distances and smoke opacity levels when no ambient light was present. The luminance contrast of the LED signs with the wall from 10 feet away was approximately 97:1 with no smoke, 7.6:1 at 5 percent smoke opacity, and 4.2:1 at 10 percent smoke opacity. The PL signs actually fared better than the LED signs in darkness, with contrast ratios of 137:1 in clear conditions, 9.6:1 at 5 percent smoke opacity, and 5.2:1 at 10 percent smoke opacity.

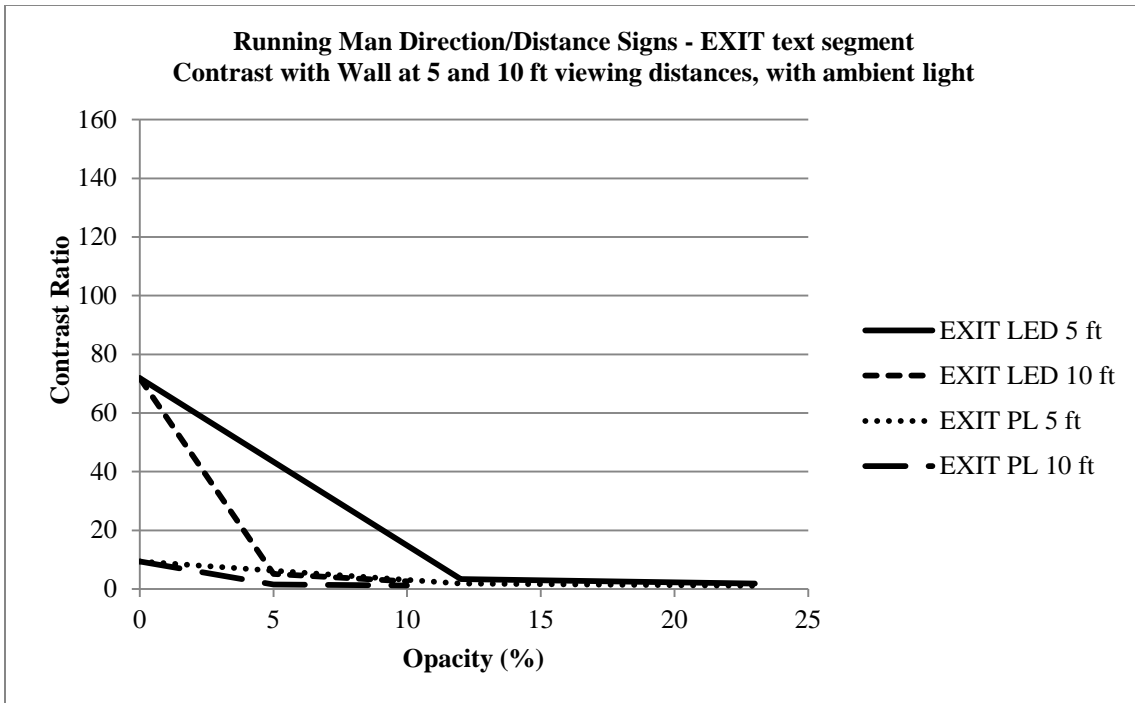


Figure 21. Contrast ratios: running man signs vs. tunnel wall, with ambient light.

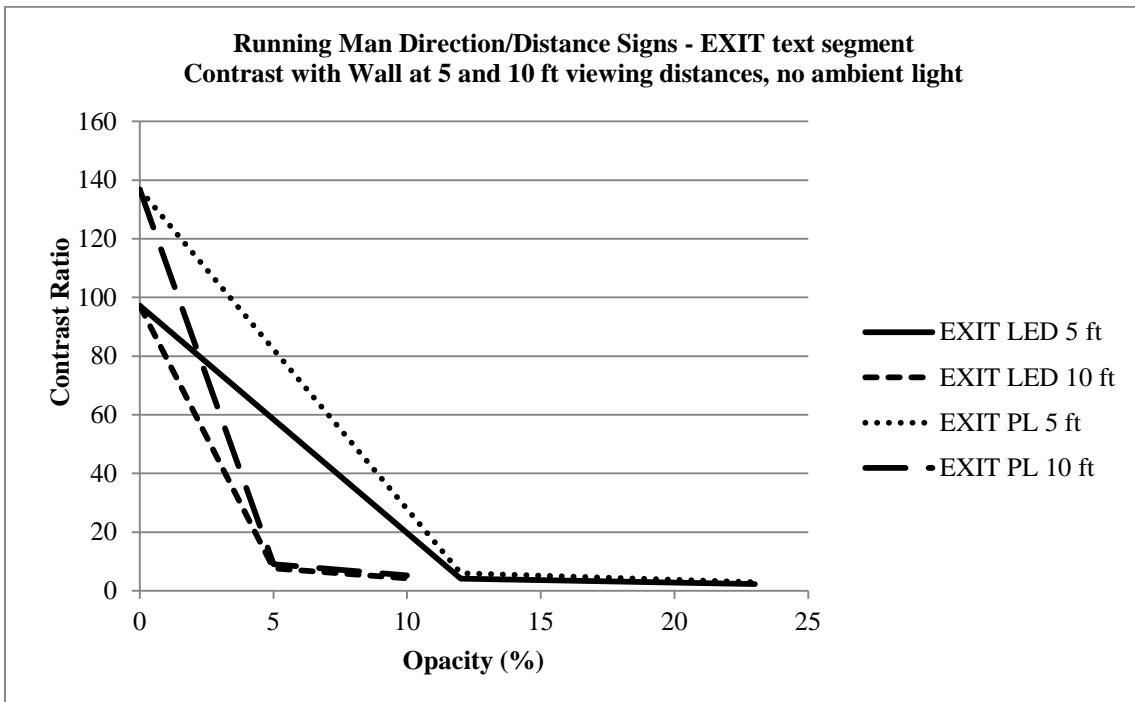


Figure 22. Contrast ratios: running man signs vs. tunnel wall, no ambient light.

Finally, the contrast ratios between the positive (brighter) and negative (darker) areas within each sign also declined with increasing smoke opacity, as shown in Figure 23. This is one metric in which PL signs surpassed LED signs in clear (no smoke) conditions when ambient light was present: the positive/negative contrast of the green “EXIT” text against the

photoluminescent background was approximately 16:1. The corresponding contrast for the LED sign was approximately 4:1. At 5 percent smoke opacity, the contrast ratio for the PL sign dropped to 1.6:1; the corresponding contrast for the LED sign was 2.3:1.

The positive/negative ratios improved in the absence of ambient light, similar to the improvement seen in the sign/wall contrasts (see Figure 24). Again, the PL version of this sign had higher positive/negative element contrasts than the LED version (likely because even the dark portions of the LED signs were somewhat illuminated by the internal LEDs, while the dark portions of the PL signs had no such illumination).

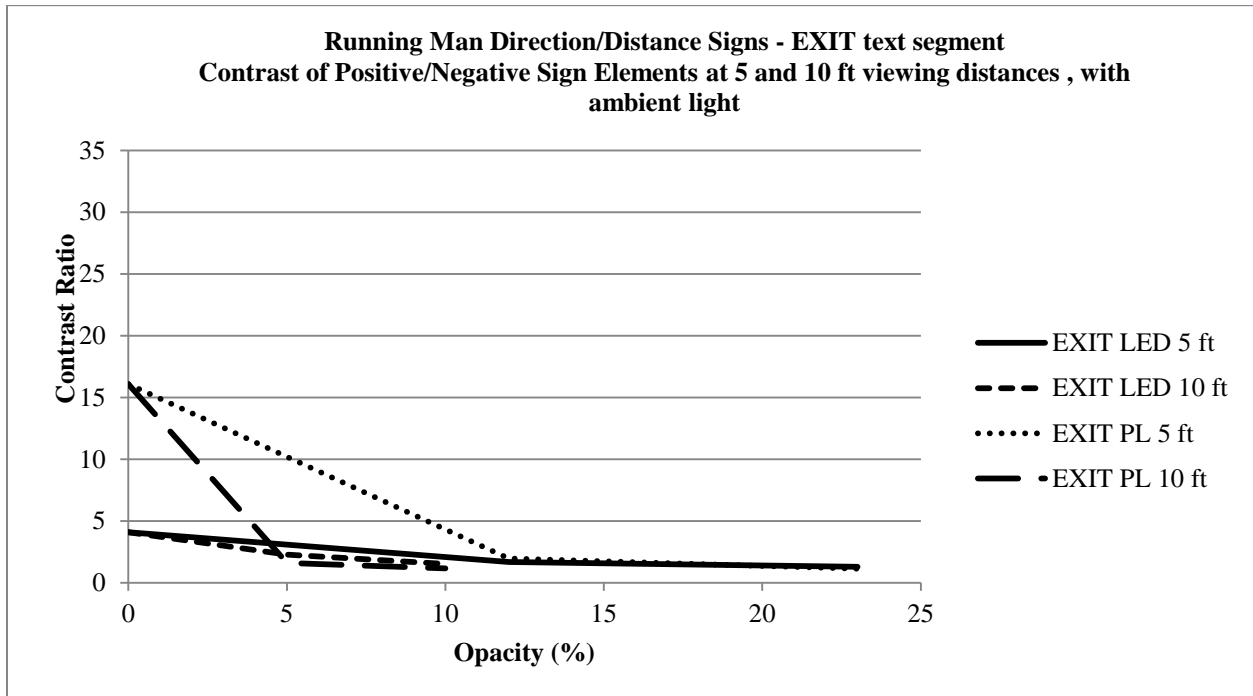


Figure 23. Contrast ratios: sign positive/negative luminance areas, with ambient light.

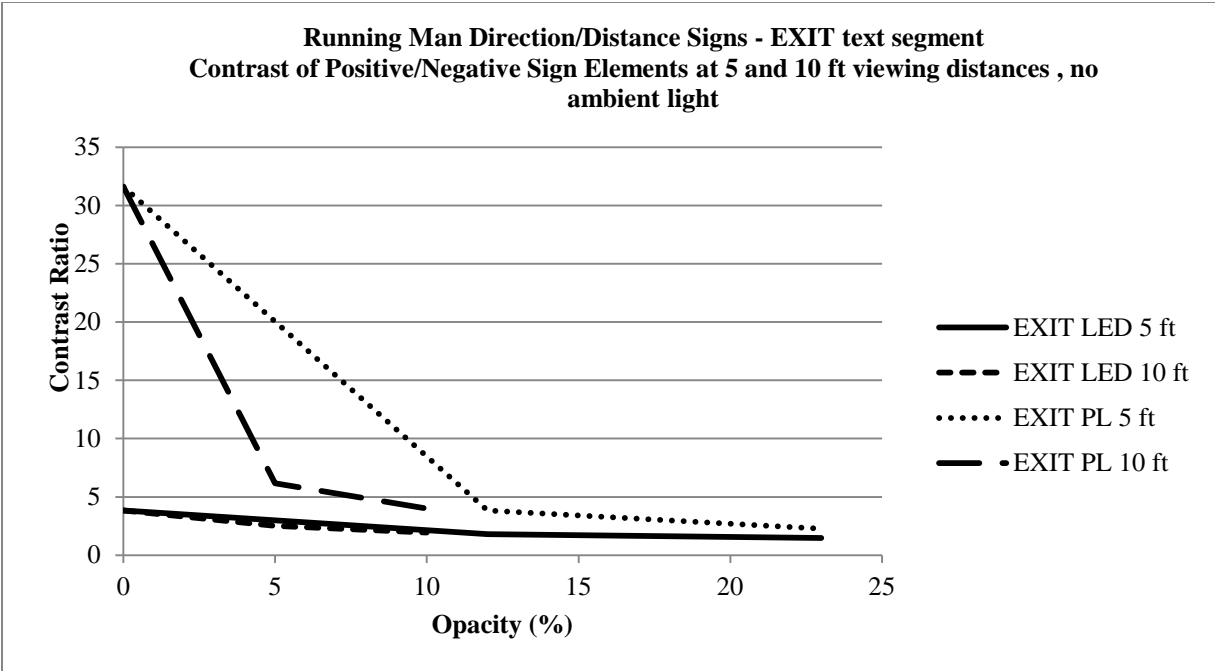


Figure 24. Contrast ratios: sign positive/negative luminance areas, with no ambient light.

All of the above descriptions focused on the negative contrast portions of the running man signs. Figure 25 compares the luminance of the LED and PL versions of the text-only EXIT signs with illuminated or photoluminescent text against a non-illuminated background. Figure 26 compares the contrast ratios of the positive and negative elements of these two signs.

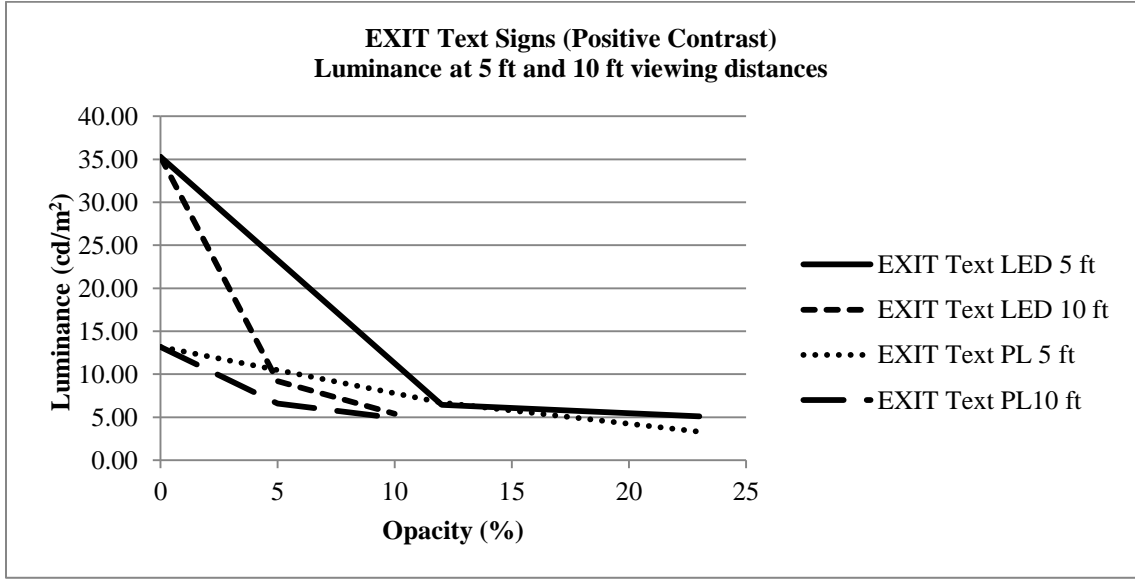


Figure 25. Luminance measurements of selected LED and PL positive contrast signs.

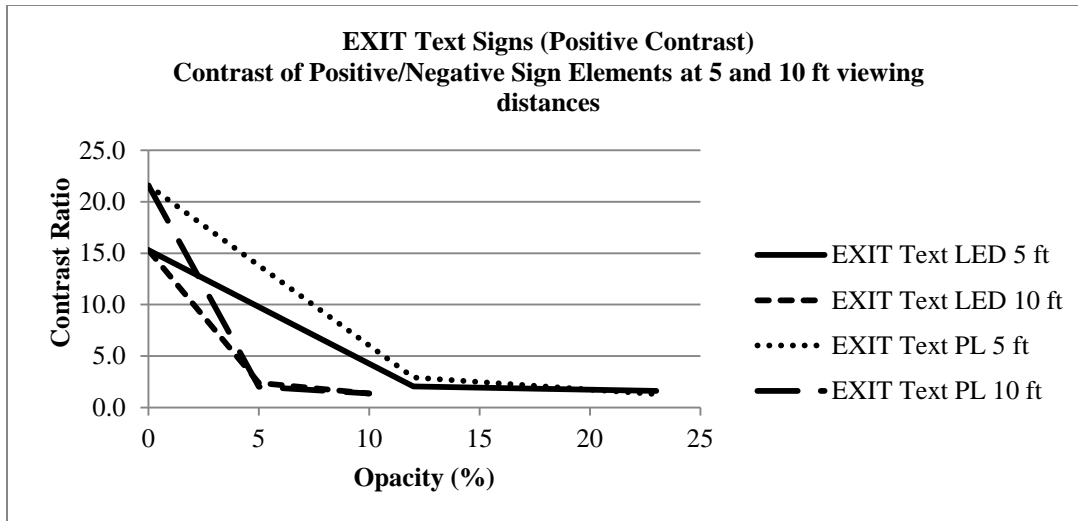


Figure 26. Contrast ratios: sign positive/negative luminance areas of EXIT text-only signs, with ambient light.

The luminance measurements all displayed some general trends that were echoed in the detection and legibility distance results in the tunnel simulation.

- All of the signs lost much of their effective luminance even with very low levels of smoke in the atmosphere. This affected how far away they could be seen and reduced the contrast between their light and dark areas, which made text and symbols more difficult to read.
- In general, PL signs began at much lower luminance levels than LED signs and remained at lower luminance levels compared to LED signs in smoky conditions. However, the differences in luminance between the PL and LED signs diminished as smoke opacity increased.
- Under low levels of ambient light, the contrast of sign luminance with the tunnel wall diminished rapidly as smoke opacity increased. In general, LED signs slightly outperformed PL signs. When there was no ambient light, contrast between the tested signs and the tunnel walls was much higher, and PL signs displayed higher contrast ratios than LED signs.
- Contrast ratios between lighter and darker regions of a sign (e.g., the contrast between a sign’s legend and its background) were consistently higher for PL signs than for LED signs. This was the case with low levels of ambient light and was even more pronounced without ambient light.

DETECTION AND LEGIBILITY DISTANCES

Detection and legibility distances were recorded for each sign that participants viewed, as well as for a photoluminescent path marking square. In some cases, detection and legibility distances for a single sign were nearly identical; this happened most frequently with single-panel signs such as the text-only EXIT signs and the symbol-only running man sign.

Participants saw treatments at varying smoke opacities, despite efforts to maintain some consistency in smoke volume and density during participant testing. The output of the smoke machine could not be precisely regulated; in addition, smoke opacity gradually diminished

within each participant’s testing period due to the movement of the participant and researcher through the simulated tunnel. With the exception of the initial running man symbol sign, which was always presented first to participants, the test signs were presented in three different orders to help balance the effects of smoke opacity across the testing sessions; however, the exact opacity percentage at the moment each sign was viewed varied from participant to participant. Because of this variance in smoke opacity, a paired t-test of the detection distances and legibility distances could not be conducted between pairs of signs. Instead, a comparison of the scatter plots and trend lines of the detection and visibility distances for each sign was conducted.

A power regression was the best fit for most of the sign detection and visibility distances through the range of smoke opacity conditions. While smoke opacities ranged from 5.6 percent to 28.7 percent (a handful of measurements with smoke opacities less than 5 percent were removed from the data set as outliers), about two-thirds of the measured opacity levels during participant testing fell between 8 and 14 percent, with a mean opacity of 10.9 percent and a median of 10.4 percent. Table 14 summarizes the detection and legibility distances predicted by the regression equations for each of the tested signs at smoke opacities of 5, 10, 12, and 23 percent. Figure 27 extrapolates the predicted detection and legibility distances for the LED and PL versions of the running man exit distance signs at smoke opacities up to 40 percent.

Table 14. Detection and Legibility Distances Predicted at Varying Smoke Opacity Levels.

Sign		Opacity				<i>R² of Trend Line</i>
		5%	10%	12%	23%	
Predicted Detection Distance (in feet)	Running Man Exit (LED)	40.4	22.4	19.2	11.0	0.84
	Running Man Exit (PL)	21.6	11.1	9.4	5.0	0.78
	Running Man Exit Distance (LED)	44.9	24.6	21.0	11.9	0.85
	Running Man Exit Distance (PL)	23.6	11.9	10.0	5.3	0.78
	Text EXIT (LED)	28.8	15.7	13.3	7.5	0.83
	Text EXIT (PL)	22.0	10.6	8.7	4.4	0.79
	Running Man Symbol (LED)	39.1	19.2	15.9	8.2	0.64
	Phone (PL)	10.1	5.6	4.8	2.8	0.36
	Refuge (PL)	12.4	6.5	5.5	3.0	0.34
	Marker (PL)	22.2	12.1	10.3	5.8	0.66
Predicted Legibility Distance (in feet)	Running Man Exit (LED)	28.9	17.7	15.5	9.8	0.57
	Running Man Exit (PL)	12.8	8.0	7.0	4.5	0.40
	Running Man Exit Distance (LED)	34.1	18.7	16.0	9.1	0.73
	Running Man Exit Distance (PL)	15.2	9.0	7.8	4.8	0.53
	Text EXIT (LED)	21.8	14.1	12.5	8.3	0.61
	Text EXIT (PL)	17.2	9.7	8.3	4.9	0.50
	Running Man Symbol (LED)	25.3	15.0	13.1	8.0	0.48
	Phone (PL)	7.6	4.8	4.2	2.7	0.35
	Refuge (PL)	8.5	5.3	4.7	3.0	0.25

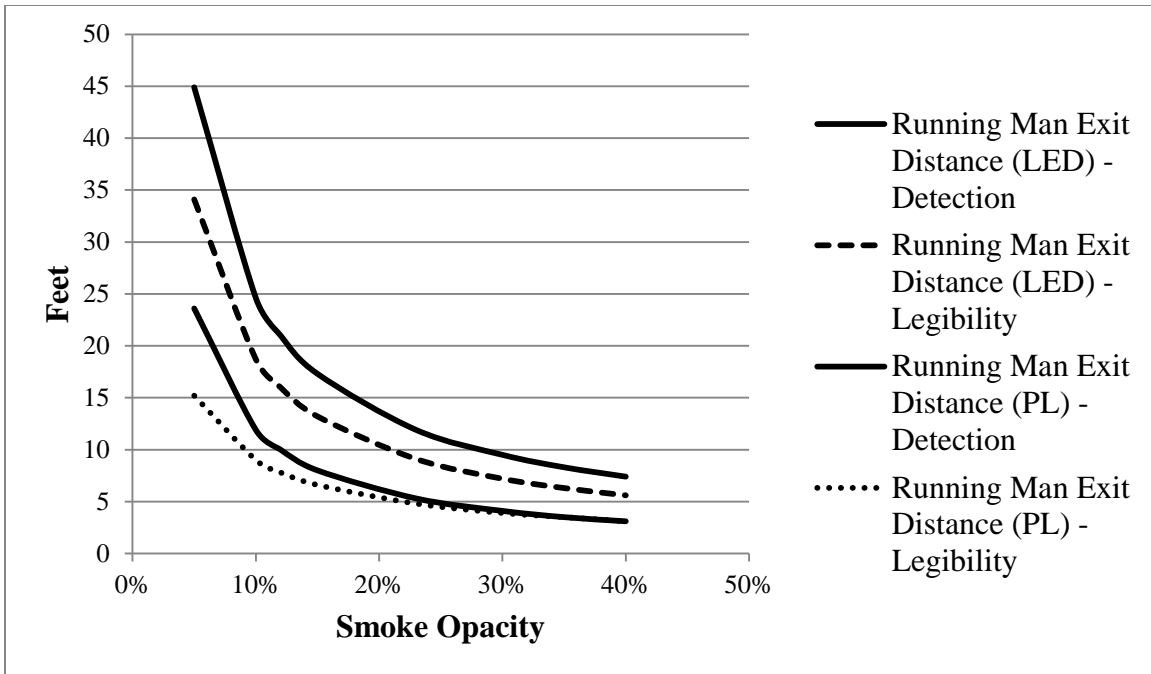


Figure 27. Estimated detection and legibility distances at varying smoke opacity percentages.

Details of the observed detection and legibility distances of tested signs are provided in the following sections.

Running Man EXIT Signs

The running man EXIT signs consisted of a running man symbol accompanied by the word “EXIT.” These signs had an illuminated (LED) or glow (PL) white background, with dark green symbols and text. Figure 28 shows the scatter plots and trend lines for the detection distances of the internally illuminated and photoluminescent versions of the signs. Figure 29 shows the scatter plots and trend lines for the legibility distances of these signs.

The regression equation for detection of the LED-illuminated running man EXIT sign ($R^2 = 0.84$) predicted a detection distance of 22.4 feet when smoke opacity was 10 percent and 19.2 feet when smoke opacity was 12 percent. Predicted detection distance for the PL version of this sign ($R^2 = 0.78$) was 11.1 feet at 10 percent smoke opacity and 9.4 feet at 12 percent opacity, approximately half the respective distances for the LED version of the sign. Greater variances in the observed legibility distances for these two signs resulted in weaker trends than those for the detection distances, but predicted legibility distances for the PL sign were also about half the distances for the LED sign at 10 percent and 12 percent smoke opacity.

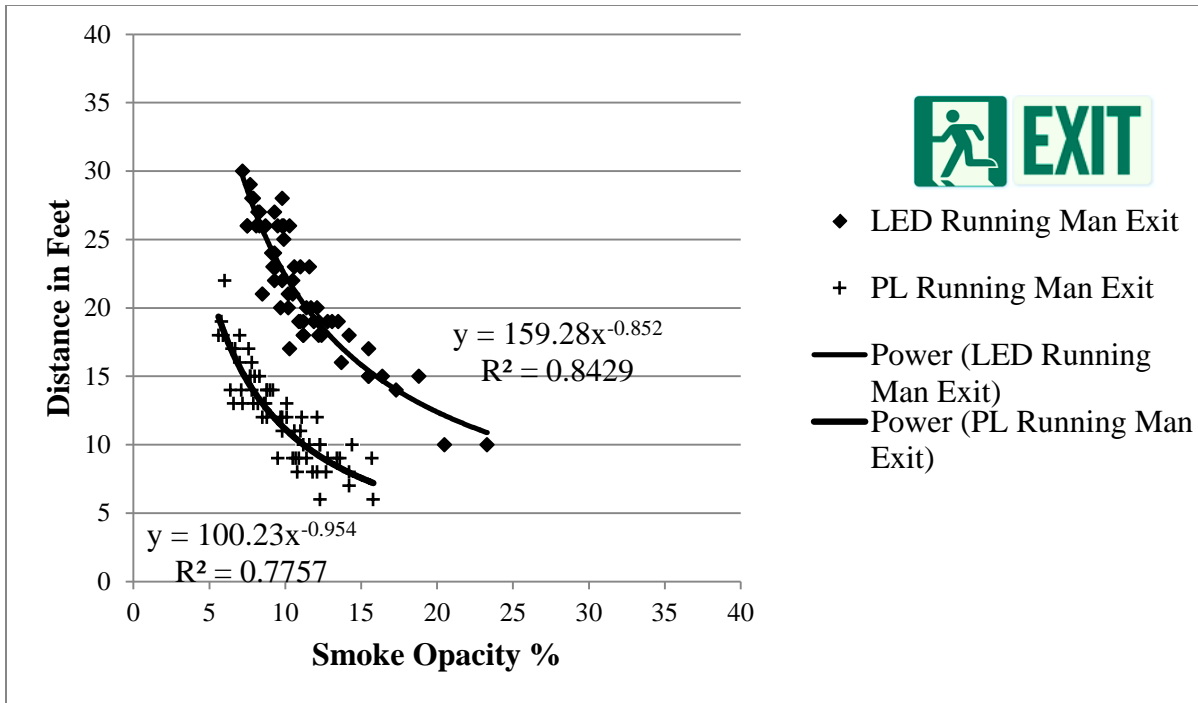


Figure 28. Detection distances for running man EXIT signs, LED and PL.

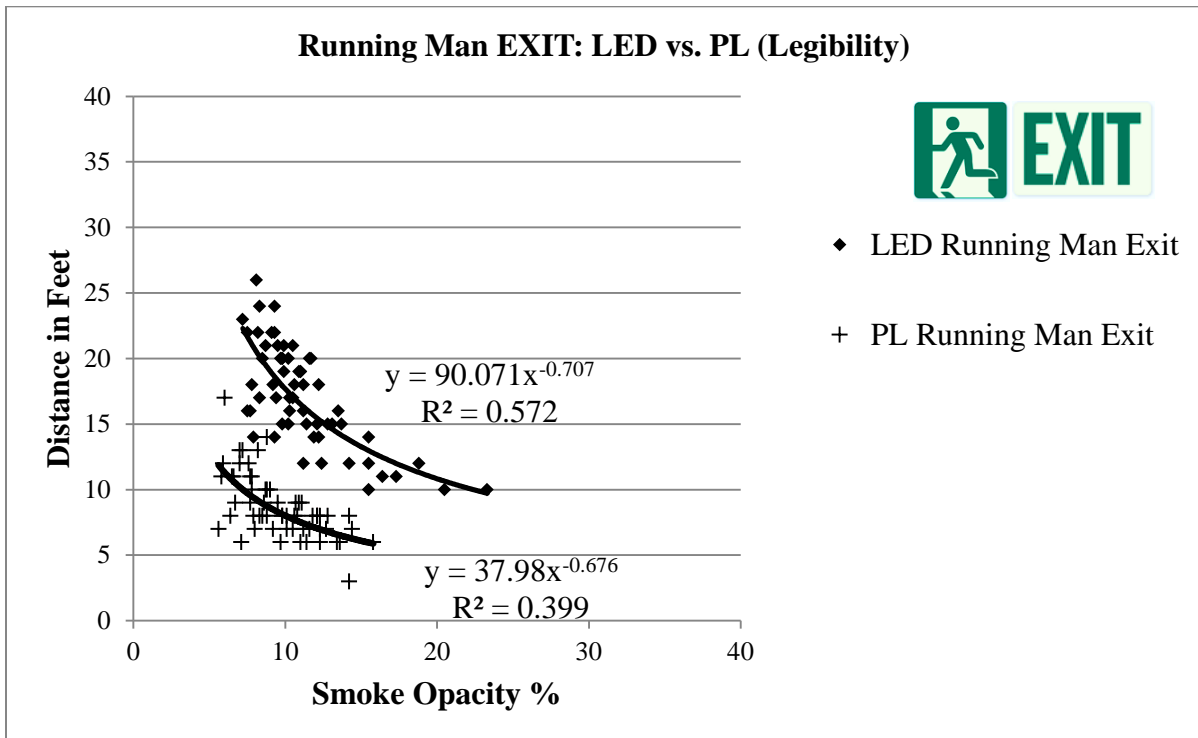


Figure 29. Legibility distances for running man EXIT Signs, LED and PL.

Running Man Directional/Distance Signs

The running man directional/distance test signs included the running man symbol and “EXIT” text, plus a distance shown in numerals and a tailed arrow pointing either left or right. Figure 30 shows the scatter plots and trend lines for the observed detection distances of the internally illuminated and photoluminescent versions of the running man directional signs. Figure 31 shows the scatter plots and trend lines for the observed legibility distances of the internally illuminated and photoluminescent versions of these signs.

The regression equation for detection of the LED-illuminated running man direction/distance sign ($R^2 = 0.85$) predicted detection distances of 24.6 feet at smoke opacity of 10.0 percent and 21 feet at 12 percent opacity. Detection distances predicted for the PL version of this sign ($R^2 = 0.77$) were 11.9 feet at 10 percent smoke opacity and 10 feet at 12 percent opacity. Legibility distances predicted for the LED version of the sign ($R^2 = 0.73$) were 18.7 feet at 10 percent smoke opacity and 16.0 feet at 12 percent opacity; the legibility distances predicted for the PL version of the sign ($R^2 = 0.53$) were 9 feet at 10 percent opacity and 7.8 feet at 12 percent opacity.

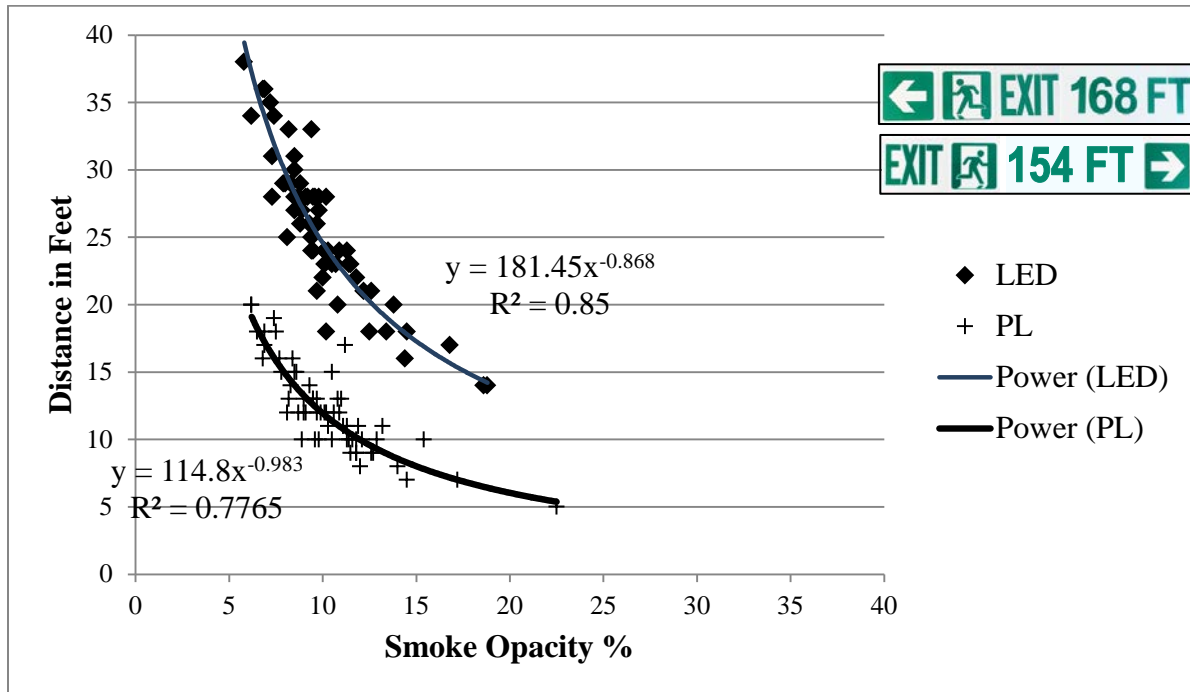


Figure 30. Detection distances for running man direction/distance signs, LED and PL.

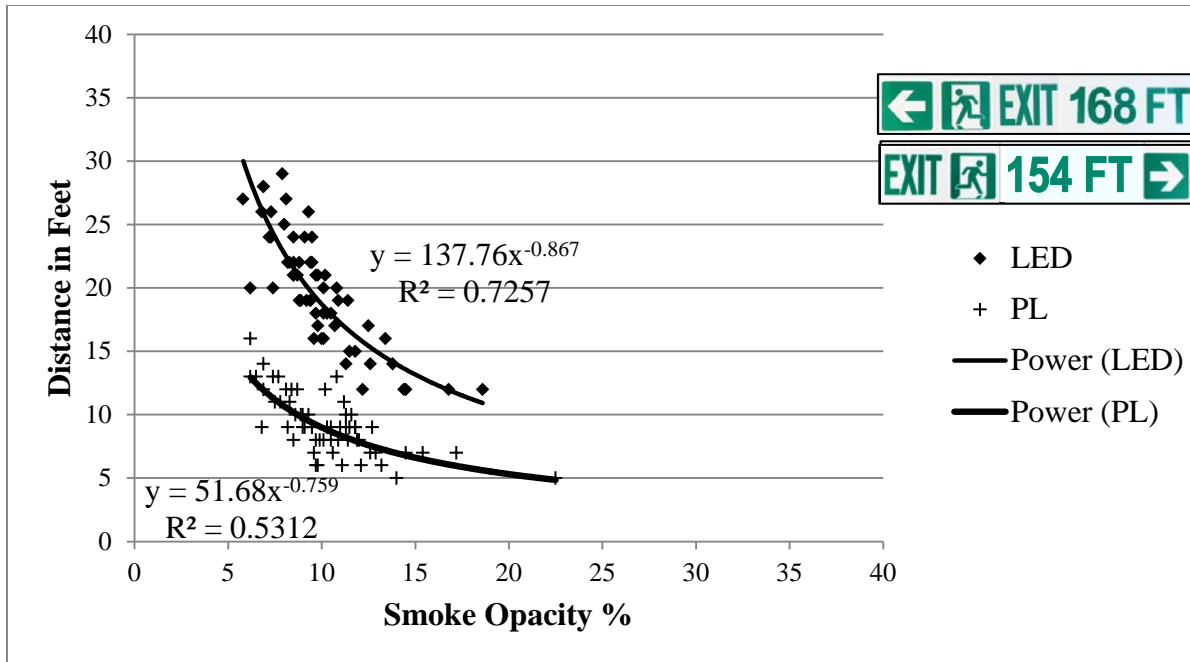


Figure 31. Legibility distances for running man direction/distance signs, LED and PL.

Text EXIT Signs

Two text-only EXIT signs with illuminated (LED) or glow (PL) letters on a non-illuminated background were tested. The LED version of the sign had red illuminated text illuminated internally by red LEDs; the PL version of the sign had photoluminescent white text. Significantly, these two signs were the only two positive contrast (i.e., illuminated text against a non-illuminated background) exit signs tested; the other exit signs were negative contrast signs, with illuminated or glow backgrounds and darker text. Figure 32 shows the scatter plots and trend lines for the detection distances of the internally illuminated and photoluminescent versions of the text EXIT signs. Figure 33 shows the scatter plots and trend lines for the legibility distances of these two signs.

The regression equation for detection distance of the LED text-only EXIT sign ($R^2 = 0.83$) predicted detection distances of 15.7 feet at smoke opacity of 10 percent and 13.3 feet at opacity of 12 percent. Detection distances predicted for the PL version of the EXIT text sign ($R^2 = 0.79$) were 10.6 feet at 10 percent smoke opacity and 8.7 feet at 12 percent opacity.

Predicted legibility distances for the LED sign ($R^2 = .60$) were 14.1 feet at 10 percent opacity and 12.6 feet at 12 percent opacity. Predicted legibility distances for the PL sign ($R^2 = .49$) were 9.7 feet at 10 percent opacity and 8.4 feet at 12 percent opacity.

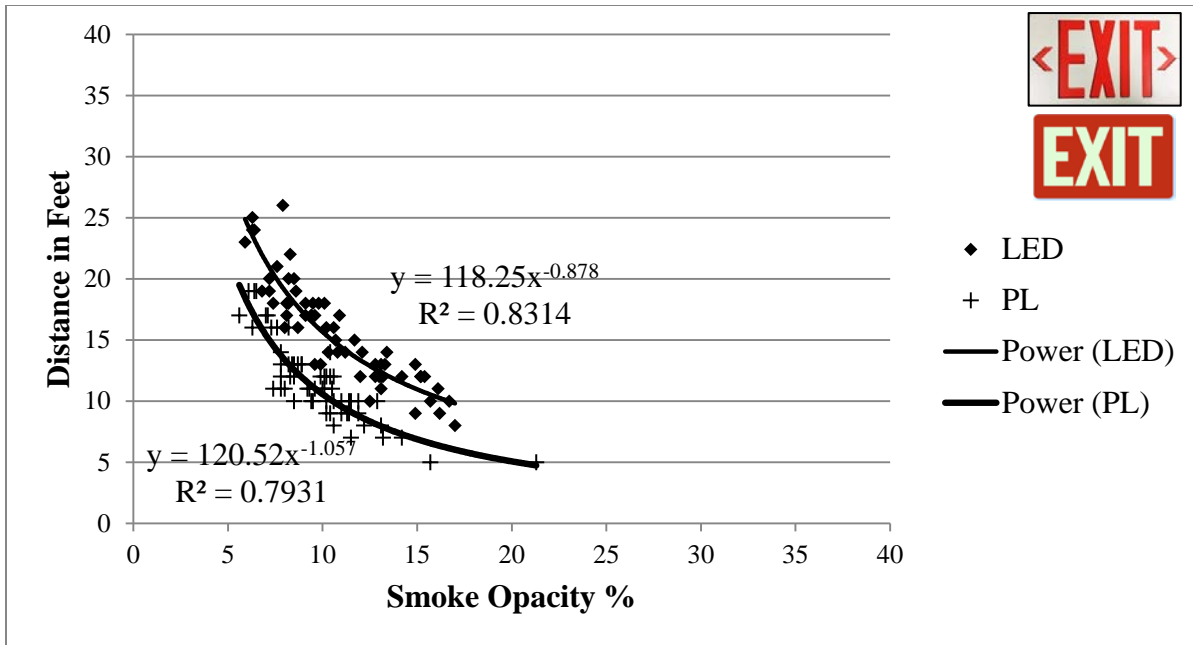


Figure 32. Detection distances for text EXIT signs, LED and PL.

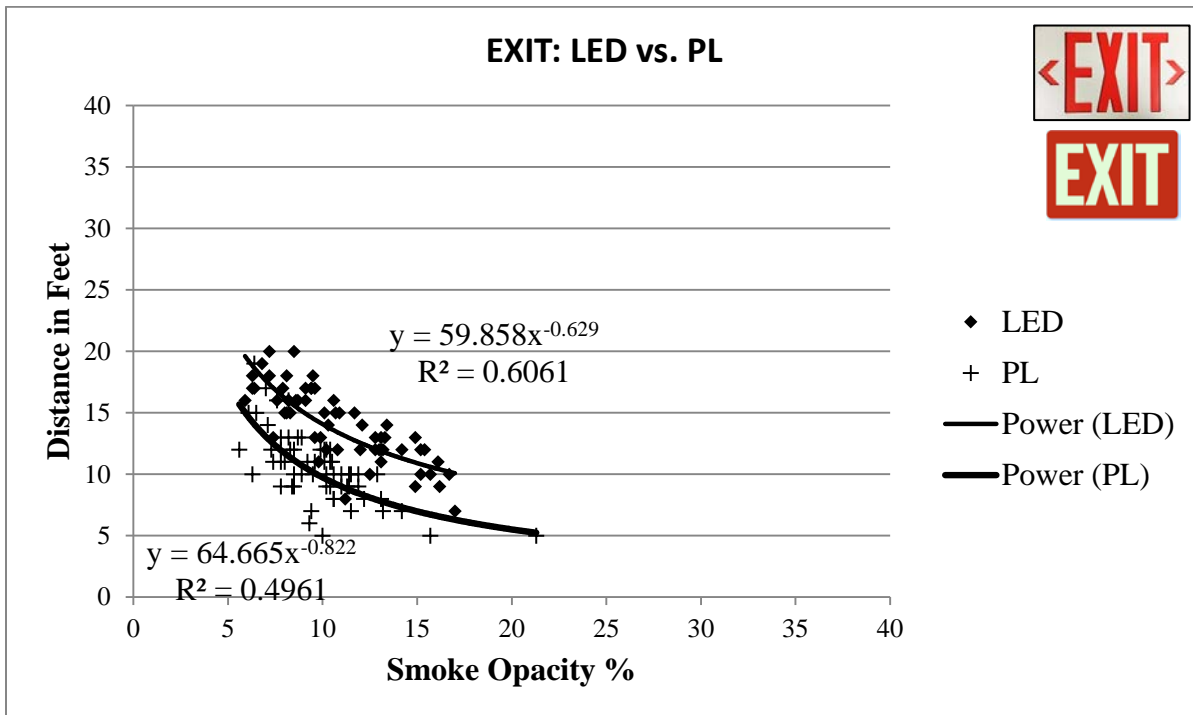


Figure 33. Legibility distances for text EXIT signs, LED and PL.

Running Man Symbol (LED)

The running man symbol-only sign was the first sign presented to participants. Because the artificial smoke in the tunnel was densest at the start of each testing session, the average opacity at which participants viewed this sign was just over 14 percent. Additionally, since this was the first sign that participants saw, it was also the practice sign: participants learned with this

first sign what to look for and where (at least in terms of height above the floor). It is not surprising, therefore, that the observed detection and legibility distances varied somewhat more than those for most of the other exit signs (see Figure 34). The regression equation for the detection distance of the running man symbol-only sign ($R^2 = 0.64$) predicted detection distances of 19.2 feet at 10 percent smoke opacity and 15.9 feet at 12 percent opacity. Legibility distances at the same two opacities were predicted as 14.9 feet and 13.0 feet ($R^2 = 0.48$).

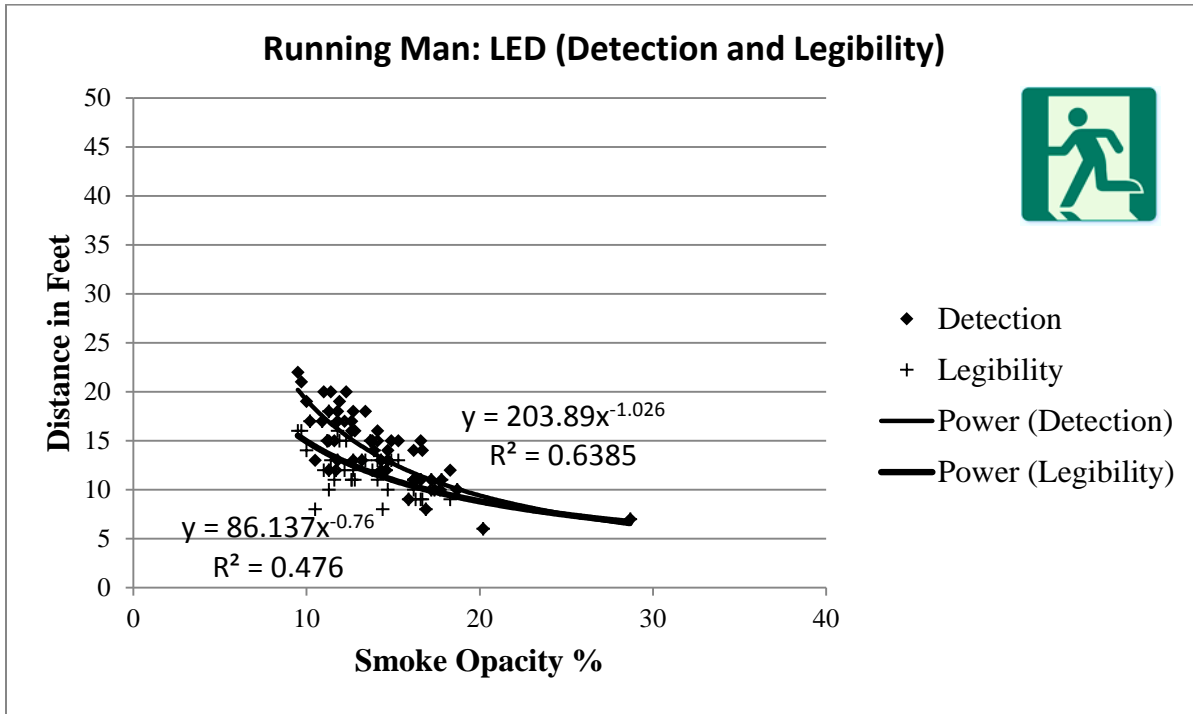


Figure 34. Detection and legibility distances for running man symbol-only sign (LED).

Emergency Phone and Refuge Point Signs

The emergency phone and refuge point signs were considerably smaller than the exit signs, and the photoluminescent material was not as powerful as other photoluminescent signs used. For these reasons, the detection and legibility distances for these signs were short, and the variability of these distances resulted in very weak regression trend lines (see Figure 35 and Figure 36).

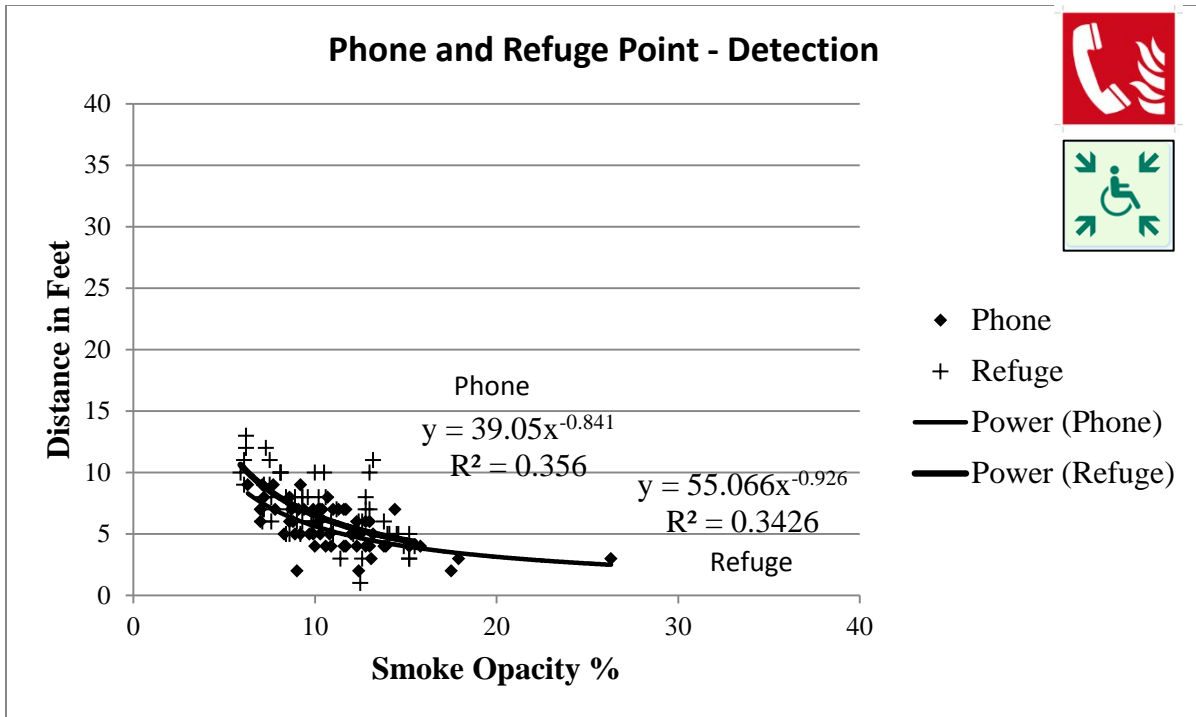


Figure 35. Detection distances for emergency phone and refuge point signs.

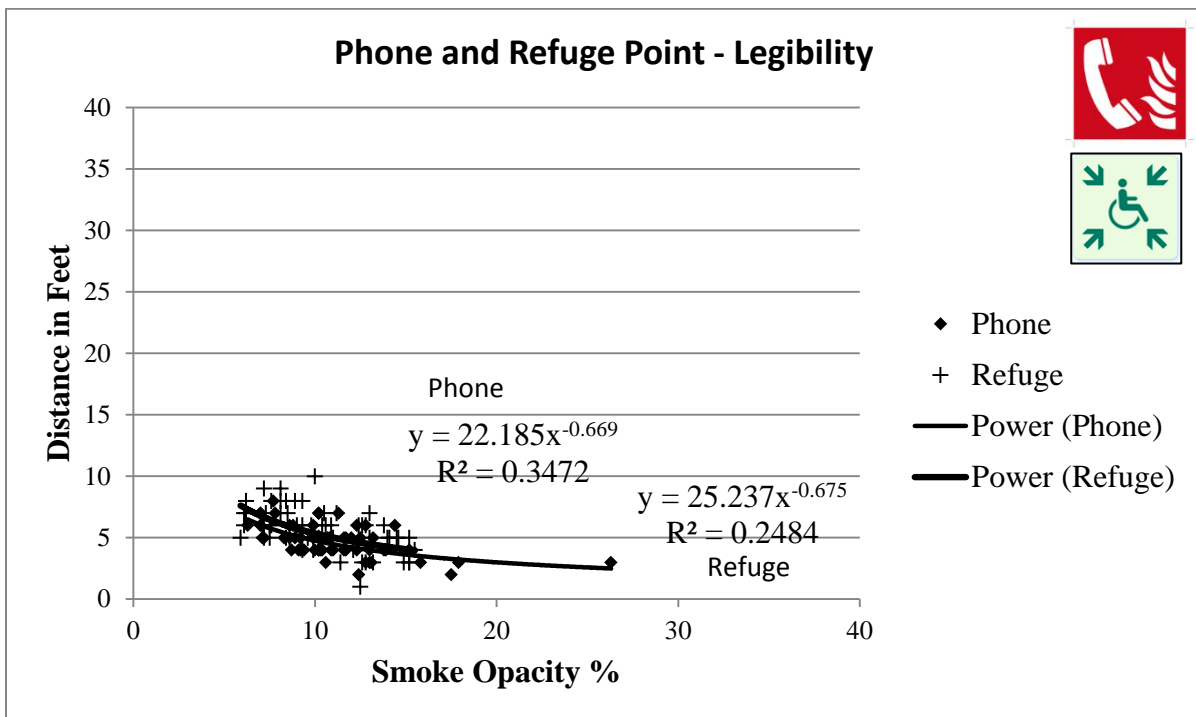


Figure 36. Legibility distances for emergency phone and refuge point signs.

PL Path Marker

Detection distances predicted for the PL path marker ($R^2 = 0.67$) were 12.1 feet at 10 percent smoke opacity and 10.3 feet at 12 percent opacity (see Figure 37).

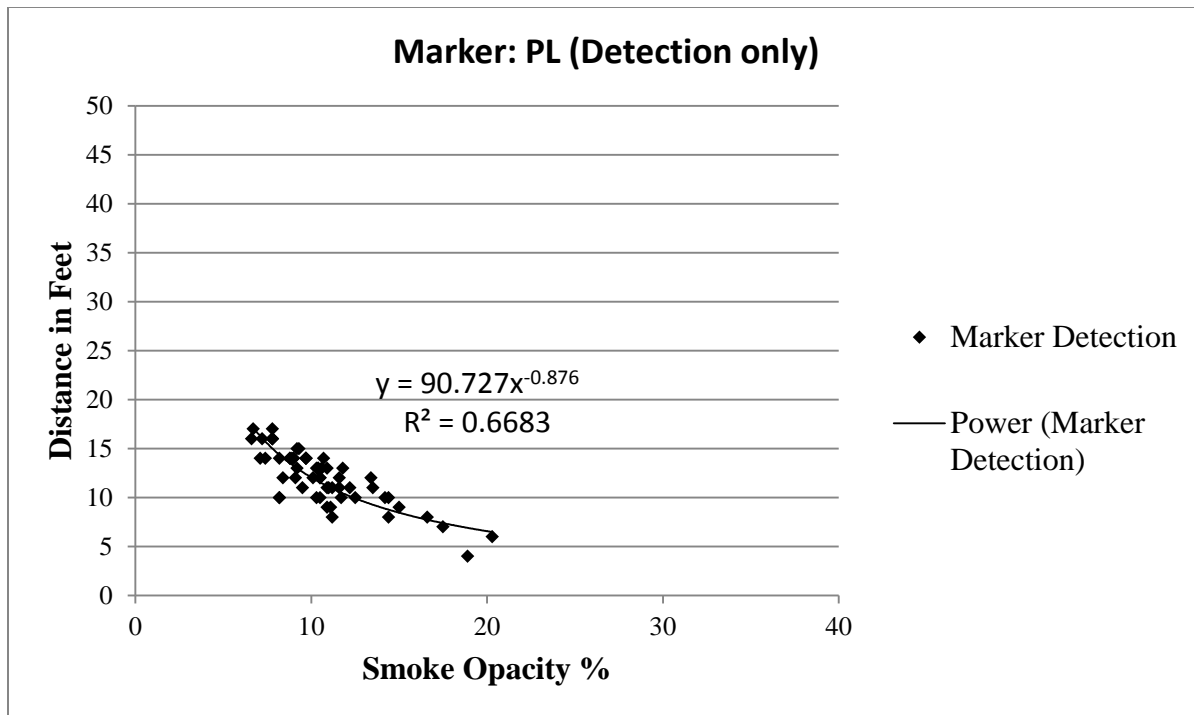


Figure 37. Detection distances for PL path marker.

PHOTOMETRIC MEASUREMENT AND VISIBILITY CONCLUSIONS

Smoke density/opacity was a significant factor in detection and visibility distances, as would be expected from the sharp drop in sign/marketing luminance and contrast that was seen in the photometric measurements. The internally LED-illuminated signs could all be seen from farther away than the photoluminescent signs; the regression equations for the detection and legibility distances indicate that most of the internally LED-illuminated signs could be detected and read at approximately twice the distances of the corresponding photoluminescent signs. An exception was the positive contrast PL EXIT sign, with detection and legibility distances that were between 60 and 75 percent of the distances for the LED version of the positive contrast EXIT sign, depending on the smoke opacity levels (the LED version of this sign, however, was also less bright than the LED versions of the running man signs).

Visibility testing with participants was done at an ambient lighting level of 10 lux measured at floor level, provided by overhead LED bulbs. Photometric measurements confirmed that even this low level of ambient lighting, when smoke was present, generated veiling luminance that reduced contrast ratios between the signs and the tunnel wall, and between sign legends and backgrounds. The measurements suggest that lowering overhead/ambient light level below 10 lux while providing brightly lit signs and path markers may improve visibility of the exits and exit paths in smoky conditions.

CHAPTER 6. CONCLUSIONS, RECOMMENDATIONS, AND SUGGESTED RESEARCH

This study focused on providing data to help accomplish the project's primary objectives:

- Determine the messages and delivery methods (visual, audible, or both) that will encourage drivers to leave their cars and exit a tunnel on foot when conditions warrant such an evacuation.
- Determine the sign graphics and colors, sign messages, marking types and colors, and auditory messages that most effectively lead people to emergency tunnel exits.
- Determine the most visible sign and marking materials and technologies for dark and smoky conditions.

Conclusions and recommendations pertaining to each of these objectives are summarized in this chapter. More detailed recommendations are presented in a proposed set of guidelines, published as a brochure, which can be found at <http://www.trb.org/Main/Blurbs/173414.aspx>.

RESEARCH CONCLUSIONS

Emergency Evacuation Messages

The literature, the focus groups, and the tunnel simulation all pointed to the value of notifying vehicle occupants of an emergency situation and providing clear directions about the appropriate course of action. The results of the tunnel emergency simulation, which presented visual and audio evidence of an unfolding fire-related emergency to participants, provided a strong indication that drivers are more likely to leave their vehicles and self-evacuate if they see or hear a message instructing them to do so.

The two messaging media tested during the tunnel simulation (DMS and audio) appeared to be equally effective in convincing participants that leaving the vehicle was the proper course of action.

Emergency Exit Sign and Marking Formats

Comprehension of the ISO 7010 running man symbol was tested in the focus groups and with the tunnel simulation participants. While a symbol-only version of the sign was understood or partially understood by approximately 86 percent of participants, most participants preferred a sign that combined the symbol with "EXIT" text. Directional signs that included the running man symbol, "EXIT" text, a directional arrow and a distance in feet were correctly interpreted by 98 percent of participants. These results indicate that a combination symbol and text sign is likely the best option for marking emergency exits in the United States, at least until the running man symbol is more widely recognized by U.S. residents.

During the tunnel simulation, the most common misconception among participants regarding the running man exit sign was that the running man symbol was next to an exit or indicated the direction of a nearby exit, versus being on the exit door itself (the text-only EXIT sign currently standard in most U.S. buildings was anticipated by most participants to be on or over the door itself). However, all signs in the simulation were placed in a frame on the wall for

visual consistency, rather than some being placed on a door; a running man sign placed on an exit door would provide visual context for this symbol that simulation participants did not have.

Seventy-five percent of participants expressed preferences for tailed directional arrows over chevron-style arrows, and a few participants did not recognize chevron-style arrows as directional symbols. Tailed arrows pointing directly left or right were clearly understood; arrows pointing directly up or down, or pointing diagonally up or down (e.g., to indicate an exit located up or down stairs), required explanation.

Of the three LED path marking formats tested, lights illuminating/strobing in a sequence that indicated a direction were the most favored by participants. Lights that flashed/strobed in unison along the path were second in preference overall, and lights that remained on (without flashing/strobing) were third.

A simulated audio beacon with a repeated “exit here” announcement was considered helpful by a majority of participants though some could not tell which direction the sound was coming from. It should be noted that the acoustics of the simulated tunnel were not the same as they would be in an actual highway tunnel.

Sign Technologies

The tested photoluminescent signs were not as bright as internally illuminated signs under the test conditions, and visibility distances were shorter on average (with low levels of ambient light in white smoke). However, the PL signs tested had higher contrast ratios between the text and background compared to LED signs, as well as greater contrast ratios with the tunnel wall versus LED signs when both were tested with photometric equipment in dark conditions.

The reduction in contrast ratios for both types of sign was due in part to light scatter off smoke particles. Visibility testing was conducted in ambient light of approximately 10 lux (typical of a tunnel under emergency lighting levels). Higher ambient light levels, such as what would typically be present in non-emergency tunnel lighting, could result in increased light scatter when smoke is present; this might have the effect of further reducing the contrast ratios and therefore the visibility of signs. A strategy that merits further exploration is reducing overhead or other ambient lighting along pedestrian evacuation paths to increase the visibility and conspicuity of exit path lights and exit signs in smoky conditions. It may also be advisable to space signs more closely together or to use lighted or photoluminescent path markings to provide additional visual cues between signs.

RECOMMENDATIONS

The study results highlighted the importance of communicating emergency information, including evacuation instructions when necessary, to vehicle drivers and occupants, and provided support for the use of the running man symbol on emergency exit signs. The study’s major recommendations are summarized below; these and additional recommendations are detailed further in the proposed guide.

Emergency Evacuation Messages

An emergency evacuation message should contain, at minimum, the following pieces of information:

- A brief statement about the nature of the emergency, e.g., “fire in tunnel” or “vehicle fire ahead.”

- Direct instructions about the action to take, e.g., “walk to exits” or “leave vehicles, walk to exits” if evacuation on foot is warranted. An evacuation direction should be specified (e.g., upstream of the fire) if applicable.
- If slightly longer messages are possible, given the medium used, it may be beneficial to include a small amount of supplementary information. Useful supplementary information can include the identity of the person or agency making the announcement and additional instructions or guidance regarding exit locations and procedures.

Emergency Exit Sign and Marking Formats

The ISO 7010 running man symbol is recommended for use on emergency exit signs for highway tunnels. An additional recommendation is to include text specifying “EXIT” with the symbol, at least until the symbol achieves wider recognition in the United States.

As specified in NFPA 502, signs indicating directions to emergency exits should be placed at least every 25 meters (82 feet) along the tunnel wall. These signs should include the running symbol and “EXIT” text, with the addition of a tailed directional arrow and the distance to the nearest exit in feet. If exits are located in two directions relative to the location of the sign, two signs should be placed side by side to indicate the directions and respective distances to the two exits.

Exit path markings are recommended to supplement directional signs in guiding pedestrians to emergency exits. Markings should be placed no higher than 1 meter (3.3 feet) from the ground or trafficway surface.

Exit doors should be marked with distinctive lighting as well as exit signs. The recommended lighting scheme is the one described by CIE 193-2010, including both illumination around the door and supplemental emergency strobe lights flashing at a rate of 1 to 2 Hz.

Auditory beacons may be beneficial as a supplemental exit door marker, depending on acoustic conditions. Auditory beacons may be used to supplement (not replace) illuminated exit door lighting and, if used, should be calibrated to be audible to listeners who are in relatively close proximity to the exit door. The recommended sound is a simple, repeated voice announcement such as “exit here,” which may be in more than one language (in addition to English).

Sign Technologies and Visibility

Because of the severe degradation of sign contrast in smoke, the designed contrast ratio between sign backgrounds and legends should be as high as possible given the materials and colors used. This is one metric in which the tested PL signs scored higher than the tested LED-illuminated signs. If internally illuminated signs are used, greater contrast can be achieved by maximizing the opacity of the negative/darker elements of the sign.

Photoluminescent signs require ambient light in order to charge. If photoluminescent signs are used for emergency exits or path indicators, it is recommended that they be selected in consultation with a manufacturer that specializes in materials for tunnel environments, taking expected ambient light levels into consideration.

Depending on the available power and control infrastructure, LED lights or photoluminescent markings may be used to delineate an emergency exit path for pedestrians. LED lights that can be controlled by tunnel operators to indicate a recommended direction to an exit (e.g., by illuminating in a sequence that indicates movement in a given direction) were

considered particularly useful by most study participants, but any marker that is visible under a variety of potential emergency conditions (darkness, smoke, etc.) should be helpful to evacuees.

SUGGESTED RESEARCH

Given the wide range of tunnel geometries and infrastructures, the myriad of possible emergency situations that may arise, and the evolving technologies for signs and markings, mass communications, and emergency management, the project team identified several potential issues that can be addressed in further detail and refined through further research. These issues are discussed in the following sections.

Emergency Announcements/Messages

The DMS messages used in this study to provide information about the hypothetical tunnel emergency to focus group and simulation participants were two-phase messages. Two phases are the maximum currently recommended by the MUTCD for dynamic signs, though that recommendation assumes three lines of text for each phase, while the DMS used in the study was a single line of text. While there might be some benefit to providing additional information (beyond the MUTCD two-phase standard) in stopped traffic conditions, there could also be the danger that people will delay taking action if they think that further information will continue to be provided on the DMS. A short, repeated message may convince people to start moving. The question of the maximum number of message phases for both normal and emergency conditions in a highway tunnel merit additional testing in the future.

Further research is needed to examine the effects of tunnel reverberation, ambient noise from traffic and from other emergency systems (ventilation fans, fire suppression systems), and other conditions that can interfere with the intelligibility of audio announcements from loudspeakers.

While the current study focused on fire as the emergency incident, future behavioral research should examine an all-hazards approach for providing messages and advisories to drivers about other types of incidents and emergencies.

Sign and Marking Formats and Placement

This study tested exit signs with 6-inch-tall text and graphics. Depending on the width of a highway tunnel, larger-scale emergency exit signs may be necessary or beneficial. A larger-scale visibility test, perhaps conducted in an actual highway tunnel or a test facility such as the Memorial Tunnel in West Virginia, would allow for a realistic comparison of different size signs.

In a two-bore tunnel with cross passages between the bores, should emergency exit signs (directing pedestrians to exit from one bore to the other via the cross passage) be placed only on the walls adjacent to the exit, or should supplemental signs be placed on walls that are opposite to exits? Signing for this and other complex tunnel geometries is another research topic that would be suitable for testing in an actual tunnel environment.

Successive signs along a tunnel passageway, for instance, distance signs showing progressively shorter distances to a tunnel exit, could not be tested within the limited space of the simulated tunnel. A larger-scale testing environment would provide the opportunity to test the effects of successive signs and markings on user comprehension and confidence regarding exit locations.

Similarly, signs showing the distances to emergency exits in two opposite directions were not tested in this study due to size constraints in the testing facility; while the study's results for

the two-directional text EXIT sign (without distances being specified) and the single-direction exit distance signs indicate that two-directional distance signs would likely be well understood, an actual test of this configuration would provide a more definitive answer.

Recent testing by the University of Greenwich in the United Kingdom found that signs with dynamic elements—specifically, signs with flashing green arrows to indicate an exit direction and signs with red X’s to indicate a route that does not lead to an exit—were well understood, were noticed by more people than static signs, and reduced evacuation time. (The Guardian, 2014) This and potentially other types of dynamic signage would be valuable to test with United States drivers.

IMPLEMENTATION OF RESEARCH FINDINGS AND PRODUCTS

As stated in the introduction to this report, there is not yet a consistent format for emergency exit signs and markings for highway tunnels across the United States. Implementing the proposed guidelines into practice and incorporating them into existing standards will require input and acceptance from NFPA, as well as from professionals and professional organizations in the tunnel and roadway operations industries and in the emergency response community. This plan proposes activities to be conducted by the research team to promote the proposed guidelines, as well as products and activities that could potentially be developed as future implementation projects.

Successful implementation of the proposed guidelines should result in widespread adoption of the running man symbol + EXIT text as the accepted format for emergency exit identification in highway tunnels in the United States. The adoption of this sign format, as well as other recommended elements such as exit door and exit path markings, is likely to be gradual as new tunnels are built and existing ones are refurbished. The guidelines may also evolve as further research is conducted (as outlined in the previous section).

Initial Implementation—Presentations and Papers on Study Recommendations

Implementation activities conducted by research team members will include development of papers and presentations on this research study and the proposed guidelines, to include the following:

- A brief PowerPoint presentation will be prepared, highlighting the study results and major recommendations from the proposed guidelines. Target audiences include AASHTO’s T-20 Subcommittee on Bridges and Structures, the NCUCTD Regulatory and Warning Signs Technical Committee, and one or more of NFPA’s technical committees if possible (502 Road Tunnel and Highway Fire Protection Technical Committee, 101 Safety to Life – Means of Egress, and/or 72 Signaling Systems—Public Fire Reporting Systems). The research team includes members on the AASHTO and NCUCTD technical committees, but not currently on NFPA committees, which may preclude the opportunity to present directly to that audience. This presentation can be prepared prior to the end of the current contract.
- A proposal will be submitted to present study findings and recommendations at the 2016 NFPA Conference & Expo (proposals due in September 2015).
- One or more papers will be written for submittal to the Transportation Research Board’s 2016 Annual Meeting and the Transportation Research Record (submittals due July 2015). The paper will be submitted to the AFF60 Tunnels and Underground Structures Committee for review.

- If permissions can be secured, a presentation focusing on the study recommendations will also be delivered as a webinar and/or conference presentation to the National Volunteer Fire Council, International Association of Fire Chiefs and International Association of Chiefs of Police, and/or the International Bridge, Tunnel and Turnpike Association (IBTTA).

In addition to the committee and conference presentations (if submissions are accepted for presentation), the proposed guidelines will be submitted as a potential annex to NFPA 502, through the NFPA’s online public input process.

Table 15 summarizes the implementation activities and expected milestone dates.

Table 15. Implementation Activities by Research Team.

Implementation Activity	Intended Audiences	Target Completion Dates
Prepare PowerPoint presentation summarizing study results and major recommendations	NCUTCD, AASHTO, NFPA subcommittees	<ul style="list-style-type: none"> • August 1, 2015
Submit paper(s) for submission to TRB	Transportation professionals	<ul style="list-style-type: none"> • July 31, 2015 – submit paper for review • January, 2016 – present paper (if accepted)
Submit proposal to present at NFPA Conference & Expo	Fire protection professionals and emergency responders	<ul style="list-style-type: none"> • September 30, 2015 – submit proposal • June, 2016 – present (if accepted)
Contact National Volunteer Fire Council, International Association of Fire Chiefs and International Association of Chiefs of Police, IBTTA	Emergency responders, tunnel operators	<ul style="list-style-type: none"> • August 1, 2015 – contact organization representatives and report results to NCHRP • TBD (based on feedback) – conduct webinars/presentations

Suggested Future Implementation Projects

The following activities are suggestions for future outreach, training, and funding programs to encourage the implementation of the proposed guidelines by tunnel operators and to expand training and education regarding emergency exit signs and markings.

- Development of a module to be used with the Federal Emergency Management Agency’s (FEMA) national incident management training when the training is being delivered to responders that have tunnels in their area of responsibility.
- A web video for drivers that educates them about the importance of having a plan to self-evacuate from a highway tunnel if needed, where to look/listen for emergency announcements when inside a tunnel, and what highway tunnel emergency exit doors,

exit path markings, and exit signs look like. Examples of similar videos include a three-video series by EastLink Tunnel Safety in Australia, viewable on YouTube.

- A laminated visor card for emergency responders, illustrating the running man exit and related emergency signs and their meanings.
- A planning template for tunnel operators that includes an assessment of existing emergency exit signs and markings in a highway tunnel and an integration plan for replacement and/or additional devices.
- Establishment of a technical services contact that practitioners can use to get guidance and assistance on implementation of emergency exit signs and markings.
- A grant program to assist tunnel operators in purchasing new exit signs and conducting training for their operators and local emergency responders.

Table 16 lists the intended audiences and potential lead agencies for the suggested implementation projects.

Table 16. Suggested Future Implementation Projects.

Implementation Project	Intended Audiences	Potential Lead Organizations/Agencies
Submit recommendations to NFPA 502 via public input process.	NFPA 502 technical committee	AASHTO T-20 Committee, TRB AFF60 Committee on Tunnels and Underground Structures, or FHWA
Module for FEMA national incident management training.	Emergency responders	IBTTA
Web video on tunnel incidents and self-evacuation.	Drivers/Public	State DOTs, local transportation and/or tunnel authorities
Laminated visor card illustrating tunnel exit signs.	Emergency responders	State DOTs, local transportation and/or tunnel authorities
Sign/marketing planning template.	Tunnel operators	AASHTO, FHWA
Technical services contact for guidance on implementation of emergency exit signs and markings.	Tunnel operators	FHWA, state DOTs
Grant program for new exit sign purchases and operator/responder training.	Tunnel operators	State DOTs

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