DIRECTIONAL SOUND EVACUATION FROM SMOKE-FILLED TUNNELS

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ABSTRACT

Fire and dense smoke in a tunnel: Can people find the way out with sound beacons over the emergency exits? A concept developed in the UK claimed 90% success but this went down to 20% if advance instruction and demonstration were omitted. The Dutch Centre for Tunnel Safety commissioned TNO to develop a self-explaining sound: directing bells and the speech fragment “exit here”. UPTUN provided additional funding. We tested the system with 75 individual participants in a road tunnel filled with smoke, visibility 1–2 m. The only instruction was to find safety and to get out of the smoke. No mention was made of emergency exits or sound beacons. Participants stepped on the roadway one by one. Most went straight to the nearest emergency exit; a success rate of 87%.

1. DIRECTIONAL SOUND EVACUATION

Smoke is dangerous in the confined space of a tunnel. The danger depends on the toxicity and the heat of the fumes. Safety measures include ventilators that should carry the smoke away in the driving direction (assuming unidirectional tunnel tubes). But smoke will continue to affect the area downstream. If that area is filled with a congestion, the motorists in that area will be in danger. Other safety measures are emergency exits giving access to spaces that are protected against smoke and heat. A critical question is whether motorists will find the emergency exits. Adequate human behaviour is a critical safety issue in time-stressed situations. UPTUN Work Package #3 devotes special attention to the human response to disaster.

Figure 1 Cars at the front gradually disappear in smoke, but the drivers happily stay seated (field study, Boer [3, 4]).

Smoke takes vision away and frightens and disorients people. Motorists will consider their car as the safest place to be and, after shutting windows and ventilation, will remain seated in their cars (see also Boer [3, 4]; Figure 1). And smoke may make it impossible to see where the emergency exits are.
Evacuation aided by directional sound seems to be the solution. Withington developed sound beacons that produced a pulsating, hissing noise (like a diligent steam engine, or like breakers on the shore but pulsating very frequently). When testing the beacons in smoke-filled environments like buildings and ships, Withington obtained success rates of over 90% (Withington [8]; Directional sound evacuation [6]). Together with professor Withington, I tested the beacons in a smoke-filled tunnel. The success rate was 69% (Boer & Withington [5], also Boer [3, 4]). The lesser success was attributed to less instruction; the test participants knew "there are sound beacons over the emergency exits" but didn't have a clue about the sound these beacons produced.
Instruction seemed to be critical. This was confirmed when we omitted the instruction "sound beacons over the exits" and just told the test participants "there are sound beacons to help you find the way". The success rate dropped to 21% (see Table 1). Some test participants pointed out that this violated their expectation of a beacon sound (unsolicited spontaneous remarks like "steam engine", "not a beacon at all"). It is even imaginable that the sound deterred people.
The necessity of advance instruction and demonstration is a weakness. At least, this was the opinion of the (Dutch) Centre for Tunnel Safety of the Civil Engineering Division of the Directorate-General for Public Works and Water Management. It is not realistic to initiate the general population of The Netherlands in the presence of sound beacons, and the sound they produce. The concept of directional sound evacuation would become much stronger if the sound would be self-explanatory like the direction "exit here". Ideally, this would be sufficient to guide motorists without any advance instruction.
"Exit here" seems simple enough but is such a speech fragment sufficient for localisation of the sound source? Auditory localisation requires adequate filling of the sound spectrum, especially in the higher areas. Withington's beacons more than satisfy that requirement; and it is not self-evident that "exit here" (or other sounds) satisfy the requirement of easy localisation.
The Centre for Tunnel Safety commissioned TNO to develop a sound that was (a) easy to localise and (b) self-explaining.

2. NEW SOUND

2.1 Criteria

The first criterion for the new sound was self-explanation; a sound that is intuitively understood without additional explanation. This rules out the use of synthetic signals. (Synthetic signals could be mistaken for warnings). We selected the spoken message "exit here" (English) alternating with "uitgang hier" (Dutch).
The second criterion was localizability of the sound; assessment of the position where the sound comes from should come effortless and easy. Withington selected noise. This is adequate but does not preclude other solutions. What is really necessary is a signal with a sufficient share of high-pitched frequencies (at least up to 16 kHz) and a sufficient density of frequency components beyond 500 Hz. This permits a wealth of signals.

The third criterion was attraction quality of the sound. Signals are often judged on well-accepted features such as loudness, coarseness, harmony, and repetitiveness. These features provide a first notion of the attraction quality of sounds. We selected a dinner-bell sound: two harmonious tones repeated on a higher pitch. People are used to hear such sounds as an introduction of a verbal message. And the speech fragment "exit here" is attractive because it is a friendly human and, moreover, a friend who knows where the escape is.
Criterion 4 was appropriateness to the situation. A verbal command preceded by a dinner bell suggests a formal and authoritative message which is exactly what the victims of a disaster need. Confusion with “natural” sounds is avoided. We also avoided sounds that were too happy or frivolous, like the sounds used in videogames.
Criterion 5 was the effect of the sound on intelligibility of other communications. During an emergency, the tunnel operator may address the motorists by the public address system (PA). Moreover, motorists will talk to one another. It is desirable that the sound beacons do not hinder any of these communications. Unfortunately, this criterion is at variance with beacons that include speech. To improve the intelligibility of other verbal communications we inserted 50% silence between the sounds of the beacons.
Criterion 6 was resistance to environmental noise such as ventilator sounds. We selected a sound spectrum that differed as much as possible from such sounds.

2.2 Dinner bells and "exit here"

The sound selected was a succession of two complex tones each with two basic frequencies (the tones "C" plus "E", followed by "E" plus "G"). All harmonics of both basic frequencies were included in the signal up to 18 kHz, with amplitude decreasing 3% per octave. The speech fragment received special processing to ensure localizability. Figure 2 shows the main characteristics.

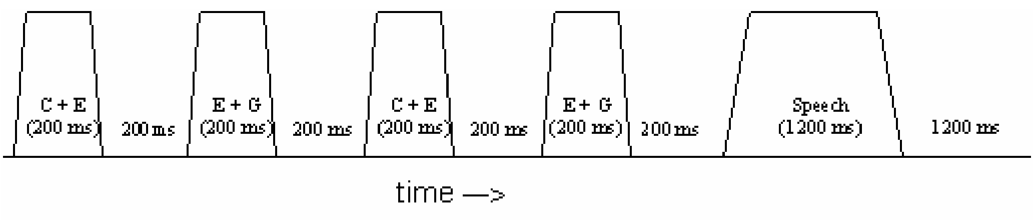

Figure 2 Amplitude of the sound of the beacon over time (50% silences; pattern repeated every 4 s; letters indicating the tones of the gamut).

3. TUNNEL TEST

3.1 Methods

3.1.1 Participants and instruction

In the night of 29 October 2003, 75 people participated. They were recruited for "escaping from a tunnel in dense smoke", should be in good health and have a driving licence. There were no hearing requirements. The age range was 18-75 years, 36.4 years on average.
After arriving on the scene, the participant read (and signed) a leaflet “You will get out from the bus in the tunnel in dense smoke. Your task is: get out of the smoke, get to safety. You are

on your own. Don't wait for others, don't offer assistance to others, don't ask others for help. Do what you feel is best."

3.1.2 Test area and supervision

Test area was the C-tube of the Benelux tunnel in Rotterdam. The C-tube is 6.6 m wide with one lane of 3.5 m, and 30-cm "barriers" on either side. There were nine emergency exits along the left wall every 100 m numbered 10, 9, 8 … 2. The distance between exits 6 en 7 was half the normal distance: 50 instead of 100 m. The exits could be opened with a normal door-handle, turned in the direction of the flight, and were self-closing. The threshold was about 50 cm above the road and access was facilitated with a step 30 cm high and a tread of 25 cm. Step, threshold, and door were 108 cm wide; the net aperture was 90 cm wide and 200 cm high. Figure 3 shows an emergency exit.

Figure 3 Emergency exit with sound beacon on top (black box; test assistants are preparing the area; smoke is starting to develop).

The test area was halfway down the tunnel, around the exits 6 and 7 (see Figure 4). Chains were stretched across the roadway 25 m beyond these exits. This protected participants from straying too far in the smoke. TNO personnel guarded the chains and the exits 6 and 7. Sound beacons were mounted above the exits 5, 6, 7 and 8.

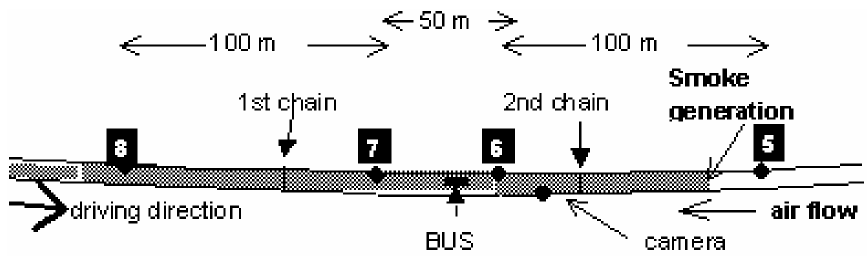

Figure 4 Test area, fenced off with chains (exits 8-5 carried sound beacons).

A thermal imaging camera was mounted 2 m high, 16 m after exit 6, looking backwards. The camera saw the wall without exits (right wall) on the left side, then the roadway, and on the right side the wall with the exits and exit 6 in particular. Figure 5 shows the camera view.

3.1.3 Smoke and masks

Further down the tunnel (at exit 5) four smoke generators ("Vesuvius") produced white "cosmetic" smoke (see Figure 6a). The participants carried elementary smoke masks over nose and mouth (see Figure 6b). The airflow transported the smoke to the test area at a speed of about 0.3 m/s.
Vision was 1–2 m at first and decreased to ½ tot 1½ m later on. The smoke reduced the lighting. Directly underneath the lamps the original illumination of 90–110 lux became 60–80 lux. The illumination on the roadway in front of the exits was reduced from 17–37 lux to 13–28 lux. The illumination of the wall around the exits was reduced from 90–105 lux to 70–80 lux. This is not very remarkable for the human eye.

3.2 Procedure

The participants arrived in two groups of 33 and 42 people, the first group around 20:00 h, the second group slightly after 21:00 h. They read and signed the leaflet in the bus. The bus drove them over to the test area. The side windows were made untransparent to prevent the participants from seeing the bus passing exits. During the 15-minute ride, the instruction was repeated, questions could be asked, and the bus-exiting procedure was described.
In the tunnel, the bus drove at a foot-pace. At the test location, the bus stopped between exit 7 and 6, its door 32 m beyond exit 7 and 18 m before exit 6. The engine remained idling to keep the interior warm. Then, the participants left the bus at fixed intervals of about 40 s. Directly before alighting, the participant donned the smoke mask and received an id-number (a small ticket). Five to 8 minutes after the last participant had alighted, the test was over and all were escorted back to the bus.

3.3 Result

Table 1 shows where the participants ended: through an emergency exit, or at the chain across the roadway. The data of the earlier study (hissing beacons) are included for comparison.

test	1st chain	exit 7	driving direction BUS	exit 6	2nd chain
B & W (old) (n=65)	29 45%	7 11%		5 8%	24 37%
current (new) (n=75)	**0** **0%**	**1** **1%**		**64** **85%**	**10** **13%**

Table 1 Results of old and current (bold) study (number and percentage of people arriving at the four possible endpoints).

We sum these data once for backward vs. forward escape (first chain + exit 7 = backward; exit 6 + last chain = forward) and another time for escape through emergency exit vs. escape over the roadway (exit 7 + exit 6 = emergency exit; first and last chain = roadway)--see Table 2. The trends are obvious: except for one, all participants went forward (99%) en 87% escaped through an emergency exit. Both trends differ significantly from the results of the old test: 45% forward vs. **99%** (test for proportions p<0.001) and 18% emergency exit vs. **87%** (*id.*).

test	direction of escape: backward	direction of escape: forward	destination of escape: exit	destination of escape: roadway
B & W (old) (n=65)	36 55%	29 45%	12 18%	53 82%
current (new) (n=75)	**1** **1%**	**74** **99%**	**65** **87%**	**10** **13%**

Table 2 Results of old and new (bold) beacons (summarised from previous table).

The camera reveals participants alighting from the bus and walking, almost all towards the camera. A few individuals hesitated over the direction but most went forward without hesitation. Forty-two participants (56%) went fairly straight towards exit 6; that is, they crossed the roadway slantwise. The others found orientation at the nearest wall (to their right, to the camera's left), sometimes touching the wall, sometimes with visual contact only (see Figure 5). Some distance away from the bus, we often saw an orientation reaction: participants turned toward their left and some held their pace or even stopped. The crossing followed sometimes directly, but others continued walking along the right wall making the crossing somewhat later. A few seemed determined to ignore their left and continued along the right wall.

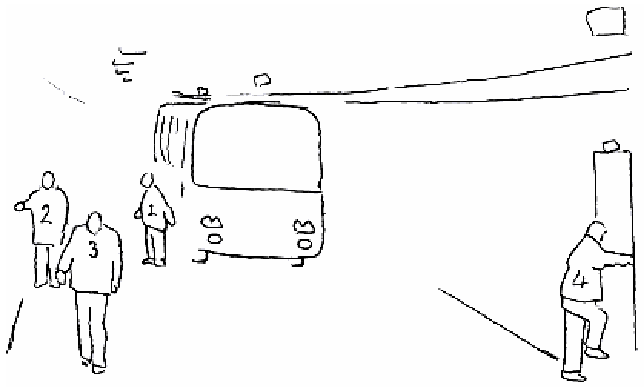

Figure 5 Camera view. After alighting (1), makes contact with the wall (2), or starts walking along the wall (3), and crosses over to the exit (4). Others walk straight, towards the exit (1 directly to 4). In the test, only one participant walked at a time.

Walking style was greatly different. The extremes were, on the one hand, a very crouched walk and (another participant) walking at snail pace with trembling hands outstretched; and, on the other hand, a very off-handed casual walk. Most walked slowly and careful, one hand outstretched. After the crossing, about five participants collided with the protruding barrier but no-one fell.

Figure 6 Smoke generation (left) and a test participant leaving the smoke-filled tunnel.

Getting to the exit took on average 23 s, which is an average walking speed of 0.9 m/s, considering a distance of about 20 m. Delays were frequently observed, however, like walking sideways to establish contact with the wall, waiting and orienting, and negotiating the doorstep. Without these delays, walking speed would be higher.

3. DISCUSSION

The new beacons were self-explanatory and could be localised easily. They guided human behaviour adequately; the success rate was 87%. This result came without any advance instruction given. Additional testimony to the efficiency of the new beacons (without advance instruction) comes from the result that all except one went to the nearest emergency which was in the driving direction.

Thermal camera observation revealed the psychological problem of leaving the "safe" wall and crossing over to the sound. Motorists with strong fear of crossing could be helped with a large arrow along the wrong wall pointing across the roadway into the direction of the emergency exit (Boer [1,2]).

Due to the way the test was set up, all participants alighted on the "wrong" side of the road; that is, all had to cross the roadway. We observed that crossing in smoke is psychologically strenuous for many because visual orientation is lost. In reality, about 50% of the motorists will alight on the side of the road where the emergency exits are. They don't have to make the strenuous crossing. It is likely that all of them would find an emergency exit. The net result would be over 90% success.

Current walking speed was about twice as fast as in the previous tests (speed towards exit 6 was 0.44 m/s in the previous test). It should be noted that speed in the previous test increased to 0.9 m/s if participants walked a 160-m distance to a chain beyond exit 8. We interpret this as psychological confidence that grows according as one continues walking without colliding against obstacles. Following this line of reasoning, the self-explaining beacons instil confidence and promote walking speed for that reason. In reality, motorists will walk in a tunnel filled with cars that may be parked untidy, and debris can lie on the road. Collisions with obstacles may occur; and motorists will loose confidence and walk with greater care afterwards. We prefer this psychological interpretation over an interpretation in terms of pure visibility (e.g., Jin[7]).

The beacons could also be effective if there is good visibility. The continually repeated "exit here" may help motorists to understand that they should leave their car and the tunnel. The beacons can thus help to overcome the initial passivity of motorists involved in a disaster.

4. REFERENCES

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