ENHANCING EVACUATION STRATEGIES: A MULTIFACETED APPROACH USING REAL TIME COGNITIVE ASSESSMENT

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DOI 10.3217/978-3-85125-996-4-11 (CC BY-NC 4.0)

ABSTRACT

This paper introduces an inventive method using real-time cognitive technology to aid tunnel operators in evaluating and enhancing evacuation strategies and safety provisions in tunnels during fire incidents. By integrating eye tracking, face emotion recognition technology, and warm smoke tests into emergency exercises, this approach highlights improvement potential in the emergency procedures (self-evacuation) as well as identifying mitigation measures and assessing the benefit of implementing them. Unlike prior studies [1], [2], [3] focusing on human attributes in evacuations, this approach emphasizes the operator's control over evacuation systems and actions, crucial in improving the safety level during an evacuation process.

This study details the application of this approach in a private UK road tunnel during a live exercise involving over 20 evacuees. Special attention is given to how safety is perceived within the bus, incident zones, cross-passages, non-incident areas, as well as at the tunnel portals and how findings were used to define mitigation measures and assess their impacts on evacuation.

Keywords: Live exercise, smoke test, evacuation process, cognitive technology, 3D modelling, eye tracking, face emotion recognition.

1. INTRODUCTION

The tunnel, as part of its overall tunnel upgrade works, instigated a project intended to explore and investigate how pre-defined emergency strategies/actions, existing life safety systems and staff competence combine to support the tunnel users (evacuees) and influence their evacuation process. While reported studies [1], [2], [3] are typically focused on the impact of human demographics, physical attributes, and other related parameters on the evacuation process, these parameters are mostly fixed in a real emergency based on the nature/use of the infrastructure. Therefore, the tunnel operator has little control over them. However, the tunnel operator does have control of how/when to deploy the different elements of the evacuation strategy (including safety provisions and actions). Understanding the impact of such actions on human behaviour is a key factor to enhance the success of the evacuation process This paper describes an innovative approach, its application and results in a UK road tunnel to support understanding of how the tunnel safety provisions and tunnel operator actions are perceived, interpreted from the point of view of the evacuee and used by them to make (wrong or right) decisions during the evacuation process.

2. UNDERSTANDING THE TUNNEL

This UK tunnel was constructed by a combination of bored and cut and cover methods. It is a twin bore tunnel with a single lane in each bore of 6.0m width. Its total length is around 1400m with a total bore width of 8.1m and a maximum height clearance of 4.7 m.

The tunnel is provided with a longitudinal ventilation system for both pollution and smoke control. The ventilation system consists of twenty-four fully reversible roof-mounted jet fans in each bore spaced at intervals through the tunnel. Control of the ventilation system is automatic for pollution control and semi-automatic in case of fire. In addition, it is provided with other safety systems such as CCTV, lighting, emergency points, emergency telephones, cross-passages, and way-finding, but no public address/ voice alarm system.

Figure 1: Tunnel layout: Cut & Cover portal and single lane layout.

3. OBJECTIVES AND METHODOLOGY

3.1. Objectives

The main objective of this study is to get a deeper insight to how pre-defined emergency strategies/actions, existing life safe systems and staff training capabilities impact on the evacuation process in case of emergency (fire). Special attention is paid to:

- Understanding how tunnel users perceive and interpret the tunnel environment, tunnel operator actions and messages (including signalling) and use this information to decide on how to react.
- Identifying potential improvement measures (operational and systems related).
- Quantitatively assessing the potential evacuation process optimization level (benefit) of addressing/implementing those improvement measures.

3.2. Methodology

Step 1: Defining the emergency scenario (live exercise), see Section 4.
Step 2: Technology set up and instrumentation, see Section 5.
Step 3: Live exercise and smart evacuation monitoring, see Section 6.
Step 4: Analysis and recommendations - the results, see Section 7.
Step 5: Assessing the potential evacuation process optimization, see Section 8.

4. STEP 1: DEFINING THE EMERGENCY SCENARIO (LIVE EXERCISE)

4.1. Emergency event

The emergency event consisted of a tunnel fire due to a vehicle crash within the tunnel. Figure 2 represents the set-up for the live exercise. The location of the vehicle crash, and therefore, location of the smoke machine, was located at 300 m from the East portal (between cross-passages 8 & 9). One bus full of passengers and one small vehicle were placed upstream of the location of the smoke machine. The bus was located next to the smoke machine to represent a worst-case scenario as smoke is supposed to reach this location at early stages and therefore compromising the evacuation of the passengers.

4.2. Tunnel users' distribution

The bus, full of passengers, and one small car were placed upstream of the location of the smoke machine to simulate vehicles unable to exit the tunnel. Participants were not aware of the nature and objective of the exercise, and the only instruction they received was to act/react as they were trained to do or as they would do in a real scenario. The following demographic participated in the exercise:

- Bus driver: 1 (male).
- Passengers: 20 (16 males / 4 females).
- No families or persons with reduced mobility were available for this exercise.

4.3. Instrumentation set up.

Nine fixed cameras were located at strategic points along both the incident and non-incident bore to capture the smoke propagation/behaviour as well as the evacuation process in real time. One thermocouple was located at the outlet of the smoke machine to monitor the smoke temperature. The location and orientation of these sensors are shown in the Figure 2.

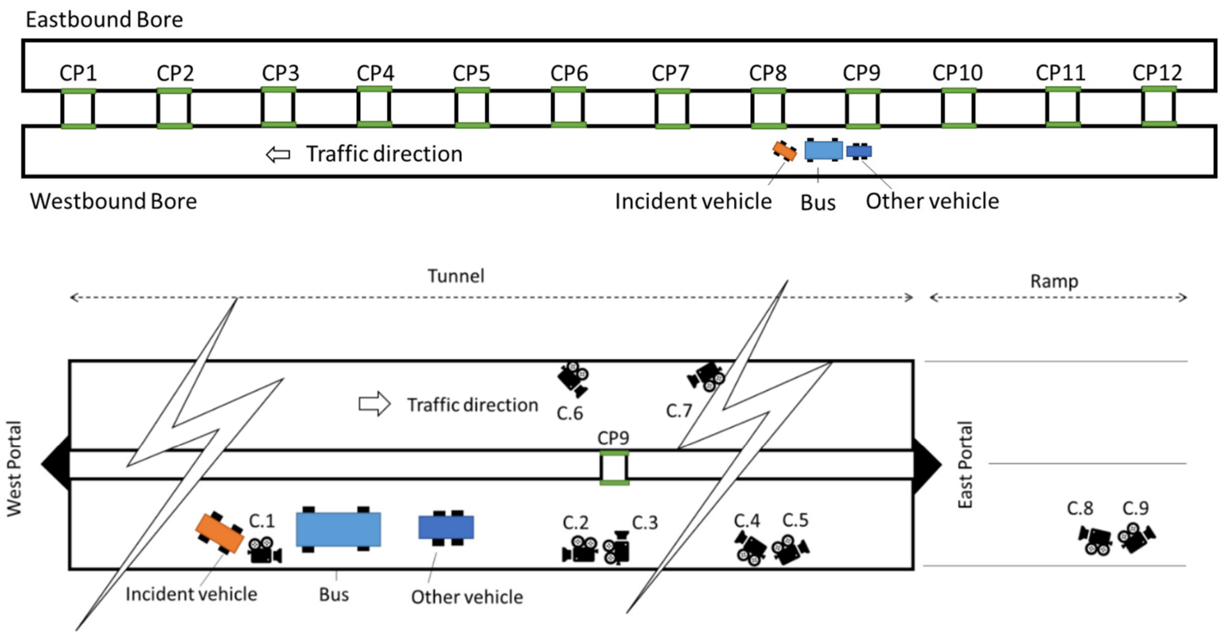


Figure 2: hot smoke machine (incident vehicle) location & the set-up for the live exercise

5. STEP 2: TECHNOLOGY SET-UP AND INSTRUMENTATION

5.1. Smoke Technology

An innovative high performance smoke generating machine (SGM), developed under a R&D framework, was deployed to create realistic and representative fire conditions and challenge the human response under low visibility conditions. During the exercise, the temperature and smoke flow at 2.1 m above the ground was set at 70ºC and 25m^3/s, respectively.

5.2. Eye tracking technology and Gaze detection, EGT

Eye tracking is the process of measuring the motion of an eye relative to the head. In this project, eye tracking technology is used with the purpose to detect the point of gaze (where one is looking, what is drawing his/her attention and for how long) during the evacuation process. Information from this stage is used to assess whether, which and how the available safety measures are perceived and interpreted by the evacuee to support their decision-making. Figure 3 shows the evacuee detecting a tunnel system during the live exercise. The red square represents the location at which the evacuee is looking (the "gaze") while eye tracking is represented in red and green.

5.3. Facial expression recognition, FER

Facial Emotion Recognition is the technology that analyses facial expressions from both static images and videos to reveal information on one's emotional state. The approach is to detect a variety of face expression patterns allowing evaluation of the emotions expressed by the evacuee during the evacuation. Information from this stage is used to assess uncertainty, confusion and decision-making moments during the evacuation. Figure 3 shows the face emotion recognition process during the live exercise.

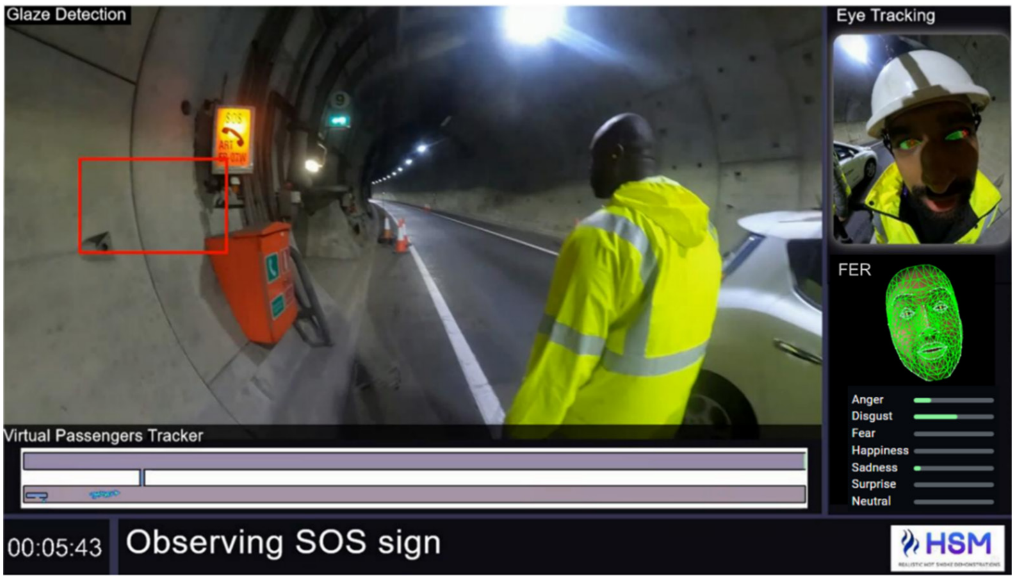


Figure 3: Eye and Gaze tracking and face emotion recognition during the live exercise. Gaze Detection Software v1.0 developed by HSM Ltd.

6. STEP 3: LIVE EXERCISE & SMART EVACUATION MONITORING (SEA)

6.1. Overview

This section describes the evacuation process during the live exercise taking insight from the instrumentation (Section 4.1), the smart monitoring system, **SEA = EGT+ FER**, (section 5.2 & section 5.3) fitted to one of the participants, and post-exercise interviews. The evacuation assessment is split in the following phases: **a**) Phase 1: Within the bus, **b**) Phase 2: Near the bus, **c**) Phase 3: Incident bore, including access to the cross-passage **d**) Phase 4: Non-incident bore and Exit portal. For clarity in the following sections "evacuee" refers to the passenger fitted with the smart evacuation monitoring device and "passenger" refers to the other tunnel users.

6.2. Phase 1: Within the bus.

The exercise started at 00:55:00. At the same time, smoke was released. Initially, the passengers were calm and relaxed. At 00:57:30, the evacuee observed the presence of smoke propagation outside the bus (Figure 4-a). In-tunnel visibility was quickly reduced to zero. The initial calm and relaxed ambience faded as the passengers became more aware of the situation. Passengers were confused with regards what to do. Some of them were sharing their concerns among other passengers. The evacuee was expecting instructions. After 3:20 mins (00:58:20), the bus driver reacted and decided to start the evacuation. He opened the door of the bus and instructed the passengers to evacuate. Smoke entered the bus door alerting passengers and the evacuee creating confusion and delay to the evacuation process (Figure 4-b).

6.3. Phase 2: Near the bus.

The passengers exited the bus to a low visibility environment. No bottlenecks were observed at the bus door. Landing in a low visibility environment provokes a feeling of uncertainty and confusion on where to go and what to do. Some of the passengers were exploring around the bus, even heading towards rather than away from the smoke source. The control room was aware of the event and the ventilation system was activated (00:59:40), clearing the smoke away from the bus location. Adequate visibility levels were recovered and helped the bus driver to instruct the passengers on the next step. However, passengers waited in this zone for around 60 secs for instructions (Figure 4-c). The bus driver was able to instruct (01:00:03) the passengers to evacuate toward to the next SOS sign located at around 60 m upstream of the bus (Figure 4-d).

6.4. Phase 3: Incident bore, including access to the cross-passage.

At 01:00:05, all passengers started to walk to the nearby SOS points taking around 40 seconds to reach this place (Figure 4-e). Cross-passage number 9 was located next to the SOS sign. Passengers remained next to the cross-passage without accessing. Some passengers tried to open the door, but they did not dare access the unfamiliar environment (Figure 4-f). After a 01:00:58 sec, one passenger took the decision, and the rest of the passengers followed him to the non-incident bore. During this phase, the bus driver was near the bus, and he was not able to aid them during this evacuation stage.

6.5. Phase 4: Non-incident bore and exit portal.

Passengers reached the non-incident bore at 01:01:20. Uncertainty on which direction to evacuate was observed. One passenger as well as the evacuee took the decision to explore the nearby area while the rest were still exiting the cross-passage. The evacuation direction was decided based on nearby wayfinding (Figure 4-g). The exit portal was reached 5.5 mins later (Figure 4-h). During this time, it was observed that the evacuee was regularly looking back and forward as he was worried about potential oncoming traffic. In addition, the evacuee was looking for tunnel signs to reassure the decision taken on which direction as well as to understand how far from the point of safety they were. During this stage, the evacuation was done in a relaxed and calm way as no major hazards were perceived by the passengers and evacuee. Once the passengers reached the portal, the group began to disperse. There was not a clear point of rendezvous for the passengers.

7. STEP 4: ASSESSMENT OF THE EVACUATION PROCESS

7.1. Timeline of events.

- Start of the exercise: 00:55:00am
- Start of releasing smoke: 00:55:00am.
- Start of the evacuation (from the bus): 00:58:53am.
- Ventilation system activation: 00:59:34am.
- Last passenger leaving the bus: 00:59:40am.
- Time to reach cross-passage: 01:00:45am.
- Time to reach non-incident bore: 01:01:20am.
- Time to reach exit portal: 01:06:50am.

7.2. Relevant findings.

The identification of the relevant findings was done by analysing the fixed cameras footage, the smart evacuation monitoring data as well as by set of interviews after the exercise. Thus,

- Passengers tended to rely on the bus driver as he was considered to have a better understanding of how to react in emergency scenarios. This resulted in 3.20 mins waiting time even if FER showed that smoke was observed by the passengers at the beginning of the exercise.
- Passengers proved to be unfamiliar with tunnel environment and emergency protocols. During the exercise, there was no clear idea on what to do at the cross passage area or where to go (from FER: "What is this door?", "Where does it go?", "Are we supposed to use it?").
- In the absence of a PA system, clear instructions from tunnel systems and personnel (bus driver) to passengers are crucial to reduce any waiting time/decision time. Around 258 sec from the total evacuation time (720s) was time in waiting for instructions and decision making.
- Well-trained personal and accurate pre-defined messages/instructions will support on improving the evacuation. Personnel escorting the passengers may have a positive effect. Specific located signs may encourage passengers to take faster decisions at those places where confusion was detected such as at cross passages.
- Wayfinding has a reassuring effect on passengers not only on the selected route but also with regards how far the exit was.
- From SEA, emotions during this exercise ranged between "confusion", "nervous" which prove that passengers were in an unfamiliar environment and uncertain on how to react but also "happiness" (smiling) which indicated that they are aware that this was a controlled exercise.

8. STEP 5: POTENTIAL OPTIMISATION STRATEGIES

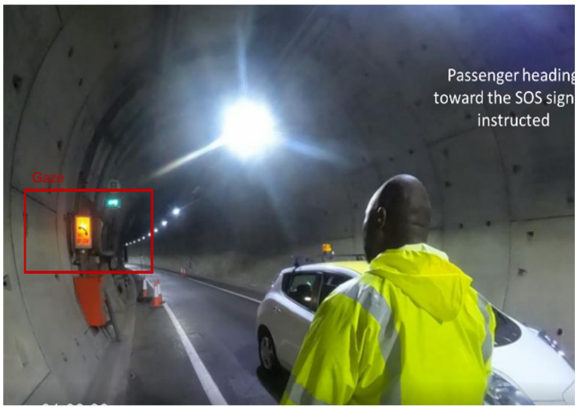
8.1. Selected strategies and applied methodology.

Based on the findings from section 7, this section is intended to assess the potential evacuation process optimisation of the current live exercise. Two main areas are identified: a) Updated communication strategies (Strategy 1) which represents a scenario where all passengers are clearly informed on what to do and where to go before leaving the bus and b) Trained Staff with updated communication strategies (Strategy 2) which represents a scenario where the bus driver reacts faster, and passengers are clearly informed on what to do and where to go before leaving the bus.

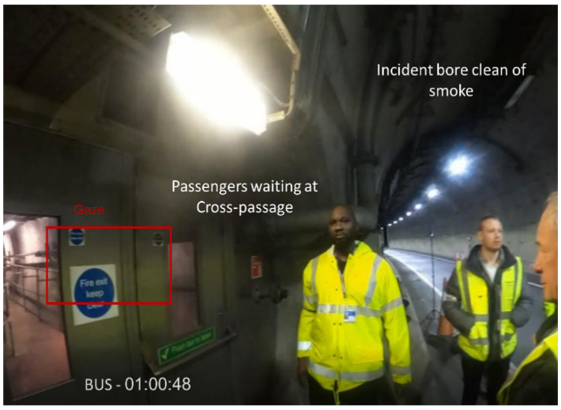
A like-for like comparison is made between the live exercise and strategies 1 and 2. For that purpose a set of 3D evacuation analysis are performed with Pathfinder. The main working assumptions are summarized below:

- Demographic distribution: as per live exercise (section 4.2).
- Walking speed: as per live exercise, defined based on the total evacuation time and evacuation distance (calculated around 1.0 m/s -1.5m/s).
- Pre-movement time: For strategy 1, the pre-movement time replicates the live exercise (3.20 mins). For strategy 2, it is based on the bus driver awareness time. 60 sec is considered at this study which corresponds to the time smoke covers the length of the bus.

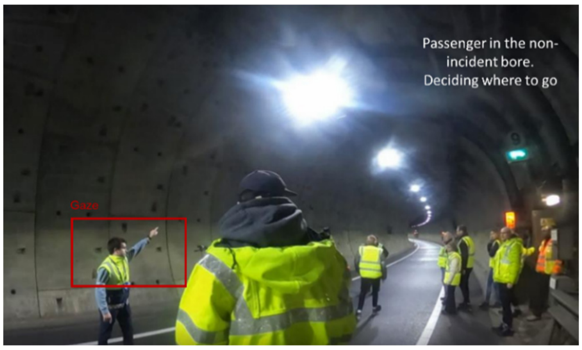
a) 00:57:30. Evacuee sitting on the bus
b) 00:58:20. Evacuation starts
c) 01:00:00. Passenger waiting outside bus
d) 01:00:03. Bus driver instructions



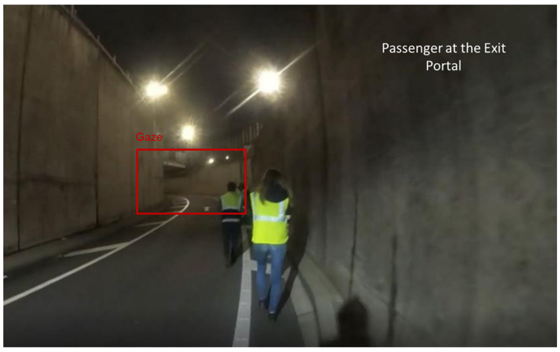
e) 01:00:33. Perceiving safety provisions



f) 01:00:48. Passengers waiting at CP



g) 01:01:20. Passengers decide which way to go



h) 01:06:50. Passengers reaching the exit portal

Figure 4: Timeline of events from the live exercise – eye and gaze tracking visualization

8.2. Optimization level estimation

The following results are observed from the like-for-like comparison between the virtualized live exercise and strategy 1 and strategy 2:

- Regarding the evacuation process to point of safety: it is observed that the evacuation time from bus to cross-passage is 387 sec, 311 sec and 135 sec for the virtualized live exercise, strategy 1 and 2, respectively. Therefore, the potential optimisation of the evacuation ranges from around 15% to 65% for strategy 1 and 2, respectively
- Regarding the evacuation process to ultimate point of safety: It is observed that the total evacuation time (from bus to exit portal) is 720 sec, 663 sec and 487 sec for the virtualized live exercise, strategy 1, and strategy 2 respectively. Therefore, the potential optimisation of the evacuation ranges from around 10% to 35%.

Figure 5 represents the evacuation from the virtualised live exercise, strategy 1 and strategy 2. The images are taken at the same simulation time (t=720 sec).

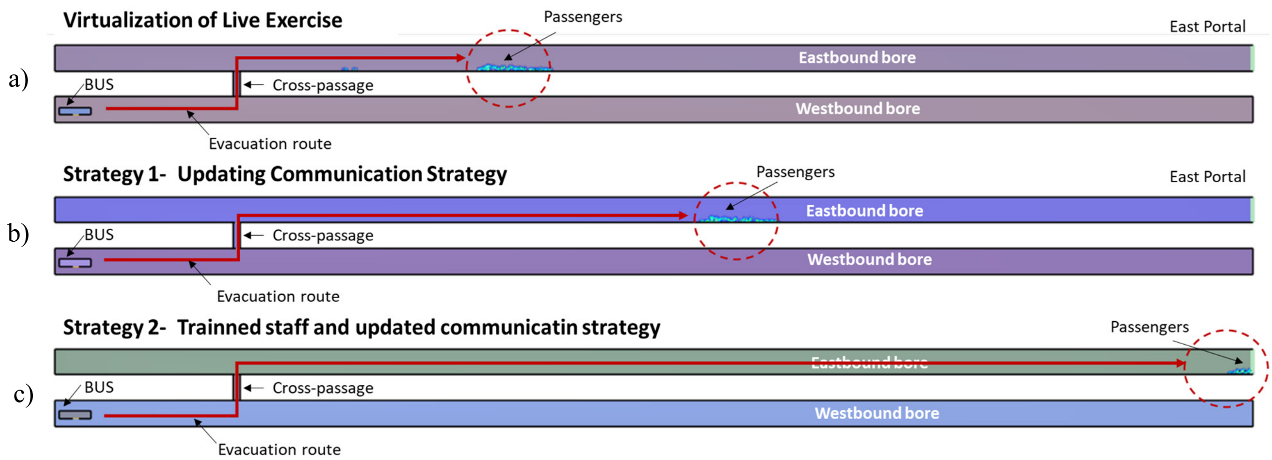


Figure 5: a) Virtualised live exercise, b) Strategy 1, c) Strategy 2. Simulated results at t=720s.

9. SUMMARY AND CONCLUSION

An innovative approach to get a better insight to how actions from the tunnel operator and safety provisions are perceived and interpreted by the evacuees has been performed during a live exercise. Cognitive technology based on eye-gaze tracking and face emotion recognition has been proven to improve the pre-defined evacuation strategy by understanding why and how passengers react in one way or another. SEA can provide a continuous follow up of the evacuation process and allows detection of moments of concern, waiting time, and decision points from tunnel users for further assessment. Simple mitigation measures such as pre-defined messages from driver, strategically located signs etc were proved to have a significant impact on the evacuation. The impact of the mitigation options can be assessed by a like for like comparison of the 3D virtualized scenario. Results can support tunnel operator investment decisions - e.g., PA design and implementation.

10. REFERENCES

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