

Safe evacuation framework with intelligent dynamic exit sign system and demonstration in tunnel fire[☆]

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ABSTRACT

Emergency exit sign systems guide occupants to safety, but they may fail in fires when smoke blocks routes. This study introduces an Intelligent Dynamic Exit Sign (IDES) system, integrating a fire-detection sensor network with dynamic sign patterns, which could enhance evacuation safety by always guiding occupants away from hazards. The system's operation framework and design rules ensure effective implementation. To address ethical concerns in complex scenarios, IDES includes a reversion mechanism that switches dynamic signs back to conventional static signs when necessary. The system's effectiveness is demonstrated through prototyping in a lab-scale tunnel model, assessing both the dynamic patterns and hardware reliability. Results show the potential of IDES to automatically optimize evacuation procedures and occupant safety during emergencies. Furthermore, the study delves into challenges associated with real-world implementation and offers insights for future applications of this innovative safety solution in more complex built environments.

1. Introduction

Increasing urbanization has led to more complex structures like high-rise buildings, large open spaces, underground infrastructures with diverse functions, and rising floorplan areas and population density. Such growing complexity of the built environment significantly increases the risk for occupants during emergencies, particularly in fire incidents [1]. The spread of fire and smoke may quickly block evacuation exits, potentially causing stampedes or severe congestion as occupants evacuate simultaneously and in a panic way [2]. Therefore, how to accurately determine safe and effective exit routes is crucial, especially given the complex nature of building egress, vulnerable people who need help, and the potential for rapid hazard escalation [3–5].

Traditional exit signs mark pre-designed exit routes established during the building's design phase, adopted globally as a critical component of building fire services systems [6,7]. These signs have batteries to power emergency lighting and maintain illumination even during power failures. Regarding their placement, emergency exit signs are categorized into two types [8,9]: one type is non-directional signs,

positioned above an exit door to indicate the exit's location, and the other type is directional signs, located along evacuation paths to guide movement towards exits.

However, traditional exit signs present two significant shortcomings. At the basic function level, their effectiveness is often negligible. Studies have shown that these signs may not be sufficiently visible or intuitive to capture occupants' attention during emergencies [10,11]. Without effectively drawing attention and indicating exit locations, the fundamental purpose of traditional exit signs is not fulfilled. Traditional exit signs fail to provide adaptive guidance at the operational effectiveness level. While these signs indicate pre-determined exit routes, they do not necessarily introduce the safest route in real-time during an evacuation because some doors may not be safe, such as if a fire is nearby [12]. This static approach can be misleading in dynamic emergency scenarios where conditions rapidly change, potentially directing evacuees toward hazardous areas.

To enhance evacuation safety, researchers proposed using dynamic exit signs equipped with extra lights and offering intuitive way-finding features to evacuees [13–17]. The signs with additional lighting

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elements (see Fig. 1) dynamically display persuasive and dissuasive patterns. Persuasive patterns are typically displayed in green, featuring directional arrows or symbols that suggest safe paths. In contrast, dissuasive patterns are shown in red, often using crosses or warning text to indicate unsafe directions. These patterns guide evacuees safely by providing real-time directions based on the location and intensity of hazards within the premises [13]. In China, the directional exit signs on the ground have been installed as compulsory for complex buildings by regulation since 2008 [18]. Still, the system is manually controlled, not coupled with a fire detection system, to operate automatically or intelligently [19]. Despite this innovative potential of dynamic exit signs being explored by academic research and adopted on limited scales, there are many unknowns regarding the performance and reliability of their practical application and critical moral issues of their failure and malfunction.

Past studies have explored the evacuation efficiency of deploying dynamic exit sign systems through experimental studies and virtual evacuation modeling [3,16,20–26]. Back in 1985, Sime [22] showed that dynamic exit signs could increase conspicuousness and break the tendency of human movement toward familiar exits. Galea et al. [21] performed a large-scale experiment in real life to investigate the performance of using dynamic exit signs in 2013. The dynamic sign system was called Active Dynamic Sign System (ADSS), with green flashing lights on the arrows of the signs. In a typical operation, the appearance of the dynamic exit signs was similar to the standard emergency exit signs. Nilsson et al. [23] conducted a real-life experiment (drill) to examine the effectiveness of using fixed dynamic exit signs over conventional static exit signs. They suggested that the persuasiveness of dynamic exit signs should increase significantly by applying a strobe or flashing green light. Later, various modelling setups were implemented across different types of virtual buildings to assess the effectiveness of dynamic exit signs compared to traditional systems. For instance, Filippidis et al. [20] utilized the buildingEXODUS system [24,25] to model supermarket evacuations, whereas Ronchi et al. [3] applied both the FDS + Evac [26] and buildingEXODUS systems to simulate evacuations in tunnel environments. While these studies provide valuable insights, it is essential to recognize that the accuracy of these simulations depends on how closely they replicate real-world conditions. This includes

addressing mechanical and technical factors that could influence the performance of dynamic exit sign systems, which are often simplified in theoretical models. Therefore, validating the findings from virtual models with real-world tests becomes crucial. Empirical testing helps to identify discrepancies between theoretical predictions and actual performance, enhancing data reliability and supporting more accurate safety regulations and design decisions.

To verify the results obtained from modelling, we applied a practical approach via prototyping to authentically evaluate the operational performance of a dynamic exit sign system, including aspects such as the system's signal latency and robustness. Kim et al. [9] constructed a prototype using Arduino to validate the communication reliability of their proposed Server-Independent Smart Exit Sign (SISES) system in a real-world setting. Similarly, Galea et al. [21] conducted research by deploying a system in a train station to observe human behavior in response to dynamic exit signs. The former study specifically focused on the latency of pattern changes via a wireless connection, and the latter focused on the performance of the signs under controlled conditions with pre-designed escape routes; however, they did not include an actual fire scenario, assuming a hazard trigger without the real presence of fire. These studies, while valuable, highlight a significant limitation in current research: the absence of real fire is considered when changing the signs' guiding direction. Future research should aim to incorporate actual fire conditions in testing to ensure that dynamic exit signs can effectively adapt to changing environments and provide reliable guidance during actual emergencies. Such studies could involve controlled burn experiments in safe environments, which would provide more realistic data on the performance and reliability of these systems.

Thus, we can identify key challenges in the research and use of dynamic exit signs, notably a lack of standardization, questionable real-life applicability, and insufficient guidelines. Researchers have employed diverse and complex building layouts in their experimental setups, leading to varying outcomes that are difficult to compare or reconcile due to the absence of standardized testing environments. These discrepancies underscore the challenge of developing universally applicable findings in this field. Regarding real-life applicability, although the shortest path concept, introduced by Dijkstra in 1959 [27], has been influential in planning evacuation routes for dynamic exit signs in

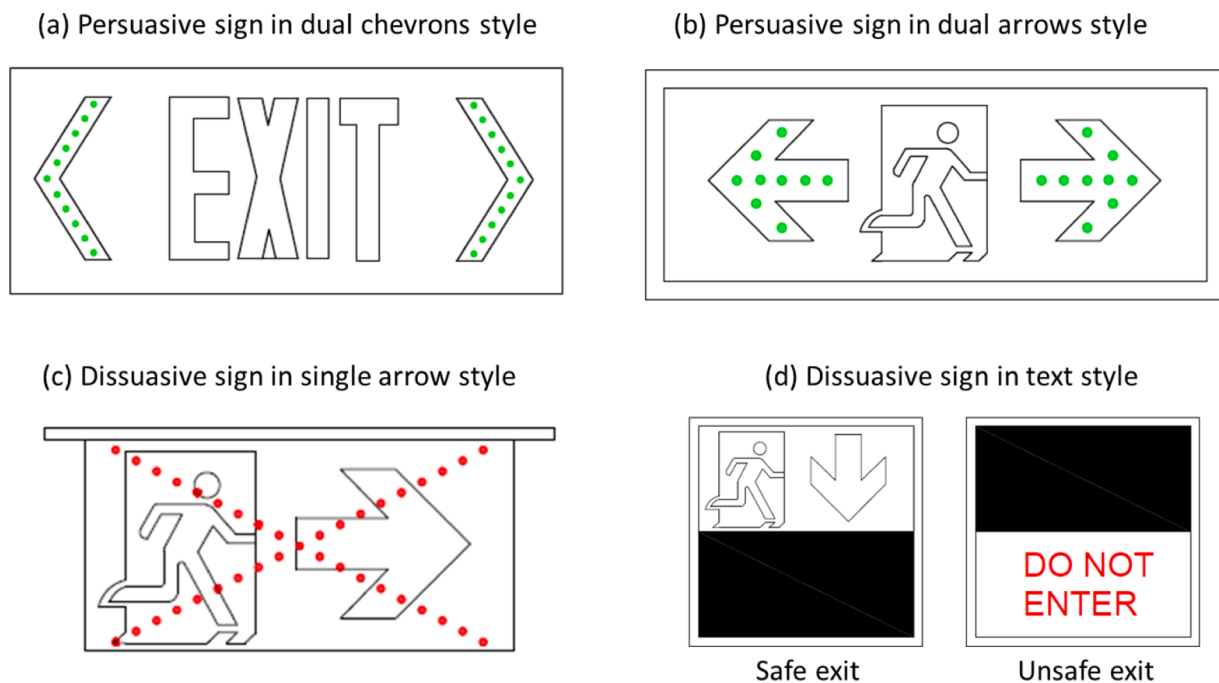


Fig. 1. (a) Persuasive sign in dual chevrons style, (b) Persuasive sign in dual arrows style, (c) Dissuasive sign in single arrow style, and (d) Dissuasive sign in text style.

virtual environments [28,29], simply adopting its standard form may lead to congestion issues in real life when multiple shortest routes converge on a single exit. Thus, a real-life system that incorporates data integration should be considered for implementation alongside Dijkstra's algorithm. Additionally, the lack of validation for a complete dynamic exit sign system in real-world scenarios has resulted in a deficiency of design guidelines and clear objectives within the existing literature. Additionally, a significant concern with implementing a dynamic exit sign system is the need to address ethical and fail-safe issues, especially when no evacuation route is completely safe. This situation occurs, for example, when an area is already engulfed in smoke or when an egress route, although nominally accessible, is perilously close to danger.

This study proposes an Intelligent Dynamic Exit Sign (IDES) system underpinned by newly established design principles and algorithms for dynamic exit signs, along with a reversion mechanism to alleviate ethical and moral issues. These principles and the reversion mechanism are applied in a lab-scale tunnel model as a demonstration and are tested within controlled fire scenarios. The response speed of the system and the feasibility of the control algorithm and design principles are demonstrated in scaled tunnel fire scenarios. Finally, critical insights into the operational performance of dynamic exit signs are highlighted for future research, and challenges for real-world application are discussed.

2. The framework of the IDES system

To effectively minimize casualties during fire emergencies, the IDES integrates both fire-risk detection and evacuation functions. The concept of the IDES system is powered by universal system components, design objectives, and rules, so it can be applicable across various types of infrastructure. Fig. 2 illustrates the framework of the proposed intelligent system, consisting of three key components:

- 1) **A Sensor Network:** The network collects real-time environmental data and is installed on the ceiling of the infrastructure before any fire outbreak.
- 2) **A Cloud Data Server:** The server receives data from the sensor network instantly. It performs analytical functions to process the

data and stores it for historical analysis and real-time decision-making.

- 3) **A Dynamic Exit Sign Network:** The network of signs updates and displays the safest evacuation routes dynamically based on the analysis from the cloud data server.

2.1. Sensor network

The IDES employs a sensor network to detect a fire event with smoke and heat by several sensors installed at the ceiling. The network is denoted as S , consisting of those individual sensor s_i (positioned at the i^{th} location within the network) that monitor smoke and heat. These sensors are interconnected to form a mesh network $G = (S, E)$, where E represents the communication links between sensors. This network is characterized by self-healing properties. The routing protocols responsible for these self-healing properties often include distributed algorithms that operate independently at each node. Each node possesses a local network view, and updates are exchanged between them to maintain a consistent and updated routing state. Protocols such as the Ad-hoc On-Demand Distance Vector (AODV) routing or the Dynamic Source Routing (DSR) are examples of such protocols used in mesh networks [30]. Therefore, this enables the network to dynamically find the shortest path $p(s_i, s_j)$ for data transmission in the mesh topology. In case of a node failure due to factors such as fire damage to a sensor s_k the network topology adjusts by recalculating paths in the graph $G' = (S, E \setminus \{e \mid e \text{ incident to } s_k\})$, thereby ensuring continuous data flow. A complete failure of a sensor node due to high heat serves as a critical indicator of severe hazard conditions. This triggers nearby sensors and dynamic exit signs to recalibrate, guiding occupants away from the danger area and enhancing situational awareness. Currently, the specific recalibration actions upon sensor failure are being explored and have not yet been implemented. A protocol will be implemented in future work where adjacent sensors intensify monitoring and dynamically adjust paths to ensure effective guidance even when individual sensors fail.

Each sensor, s_i , is programmed to activate upon exceeding predefined thresholds for smoke and heat, denoted as θ_{smoke} and θ_{heat} , respectively. These thresholds comply with the fire code and infrastructure-specific

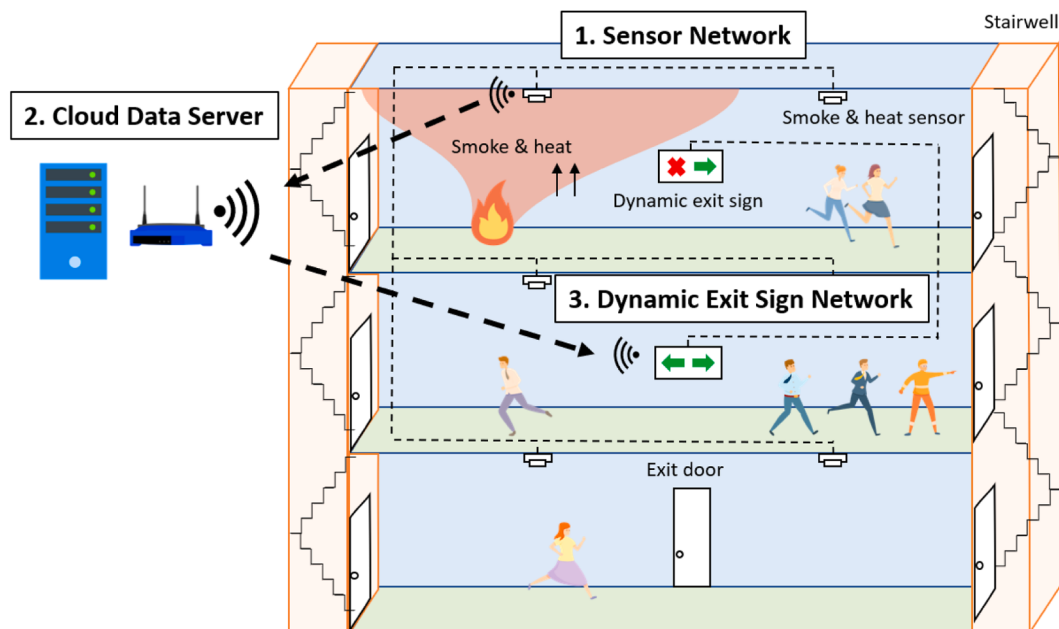


Fig. 2. Illustration of IDES with three components for fire-risk detection and guided evacuation in a building.

requirements. The network mainly operates in a low-energy **standby mode** to conserve the power supplied by internal batteries, which includes two conditions $c(s_i, t)$. In standby mode, each sensor remains inactive, not broadcasting any data initially. Periodically, at regular intervals denoted by Δt , the sensors briefly activate to broadcast status data to the server. This activity lasts for only a few seconds, ensuring efficient use of energy while maintaining timely data communication. As illustrated in Fig. 3(a), this broadcasting schedule is represented as a time-dependent function by $c(s_i, t)$, where s_i represents a specific sensor, and t denotes time.

$$c(s_i, t) = \begin{cases} \text{no broadcast,} & \text{if } t \text{ is not a multiple of } \Delta t \\ \text{broadcast,} & \text{if } t \text{ is a multiple of } \Delta t \end{cases} \quad (1)$$

This schedule distinguishes between two modes: normal as standby mode, as stated above and emergency. If the detected smoke or heat data exceeds θ_{smoke} or θ_{heat} , the network transitions to an **emergency mode**, activating the dynamic exit sign system to initiate prompt and effective evacuation procedures. The spatial arrangement and quantity of sensors are guided by local fire codes and specific safety requirements. Each sensor s_i is strategically linked to at least one predetermined escape route leading to an exit. Fig. 3(b) highlights the spatial arrangement and operational linkage of sensors within the environment. Sensors are distributed according to local fire safety codes and the specific requirements of the structure. Sensors installed at the exit doors, designated as Exit Sensors s_E , where $s_E \subseteq S$, are strategically positioned to monitor their respective exits. Each sensor's coverage area, as specified by the manufacturer, ensures that all escape routes are effectively observed and secured (refer to Fig. 3(b)).

These sensors play a critical role in providing real-time status updates on exit accessibility. The manufacturer-defined coverage areas for each sensor ensure effective observation of all escape routes, preventing blind spots. Note that the coverage area requirements for smoke and heat detectors vary by country and the type of infrastructure. For example, according to NFPA 72, the National Fire Alarm and Signaling Code, the recommended spacing between smoke detectors in rooms with smooth ceilings up to 3 m high can be up to 9 m, with adjustments based

on the sensitivity and type of detector used [31]. In contrast, regulations in Hong Kong, China stipulate that the horizontal separation between any point in a protected area and a smoke detector must not exceed 7.5 m, while the horizontal separation between any point in the area that requires protection and a heat detector should be < 5.3 m [32]. The choice between installing smoke detectors or heat detectors also hinges on regulatory requirements. For instance, in Hong Kong, China, regulations mandate the installation of smoke detectors in residential flats that feature open kitchens [33].

2.2. Cloud data server

The cloud data server of the IDES serves as the key unit for data storage and processing, as illustrated in Fig. 4. Under the **standby mode** of the sensor network, this server systematically collects and stores temperature and smoke readings from the sensor network at set hourly intervals for system documentation. These readings are stored in a structured database using Structured Query Language (SQL), which facilitates efficient data storage and query capabilities. For ease of regular access and review, the data is extracted through a web dashboard or specialised software application that provides visualisations to scrutinise the data, identify trends, and evaluate the system's responses to various conditions.

When switched to **emergency mode**, the interval for data collection changes to seconds, balancing the need to track the fire's progression using multiple sensors across the infrastructure with the server's capacity for real-time processing. The data is processed in real-time at the server to determine the display pattern on each dynamic exit sign. In envisioning the future capabilities of this system, an advanced level of operation is proposed, where the server would integrate data from occupancy sensors and Closed Circuit Television (CCTV) systems. This integration would create a comprehensive dataset, enabling algorithms to model fire spread and dynamic evacuation scenarios accurately. Such developments would allow the system to predict the fire's path and adaptively update evacuation routes in response to changing conditions. However, it is important to note that these enhancements represent

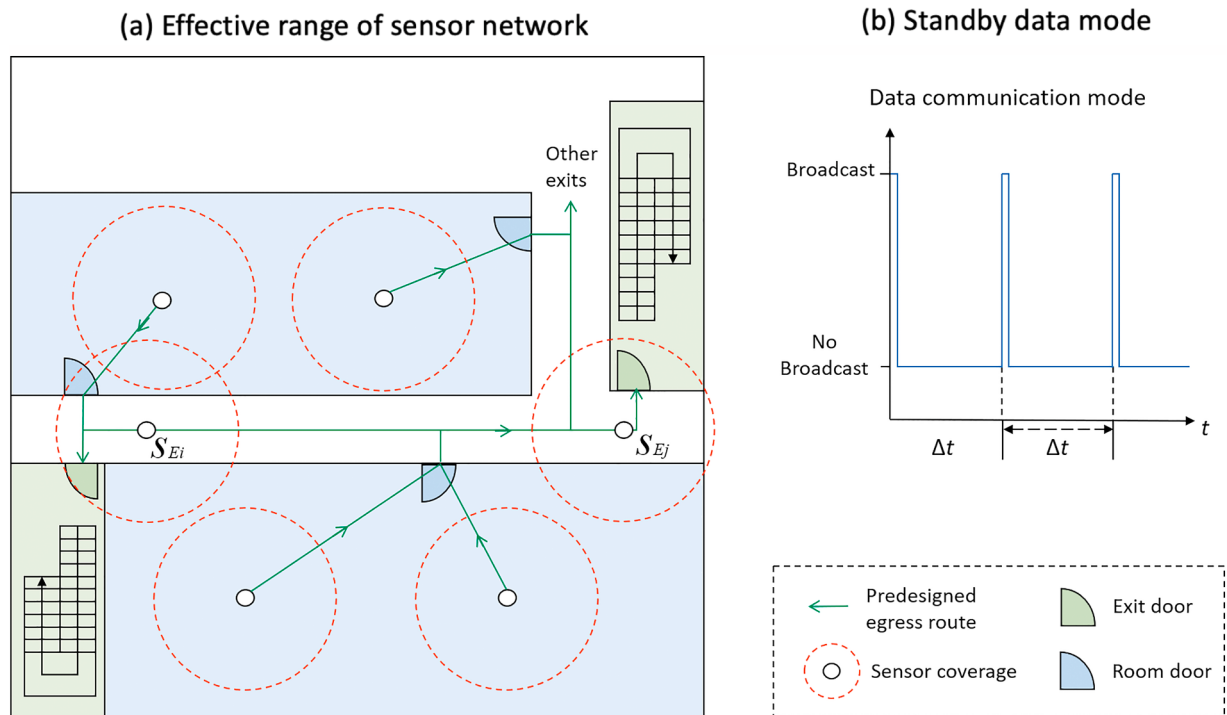


Fig. 3. IDES sensor network and data communication (a) the Sensor Network positioning of the IDES system and (b) The Sensor Network change of conditions in standby mode.

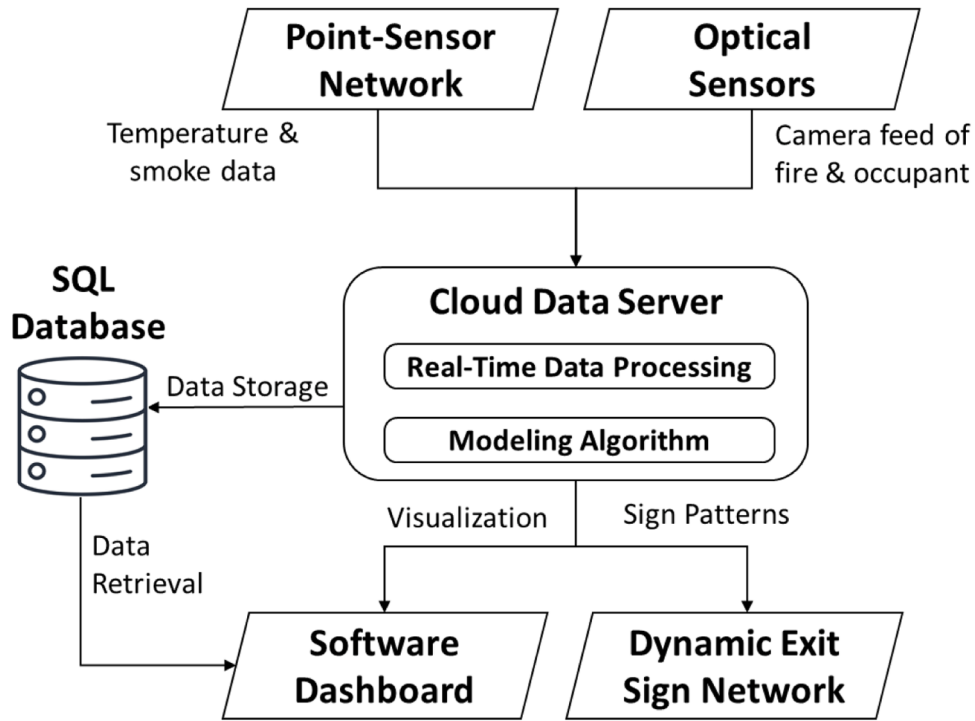


Fig. 4. Data flow and processing diagram of IDES.

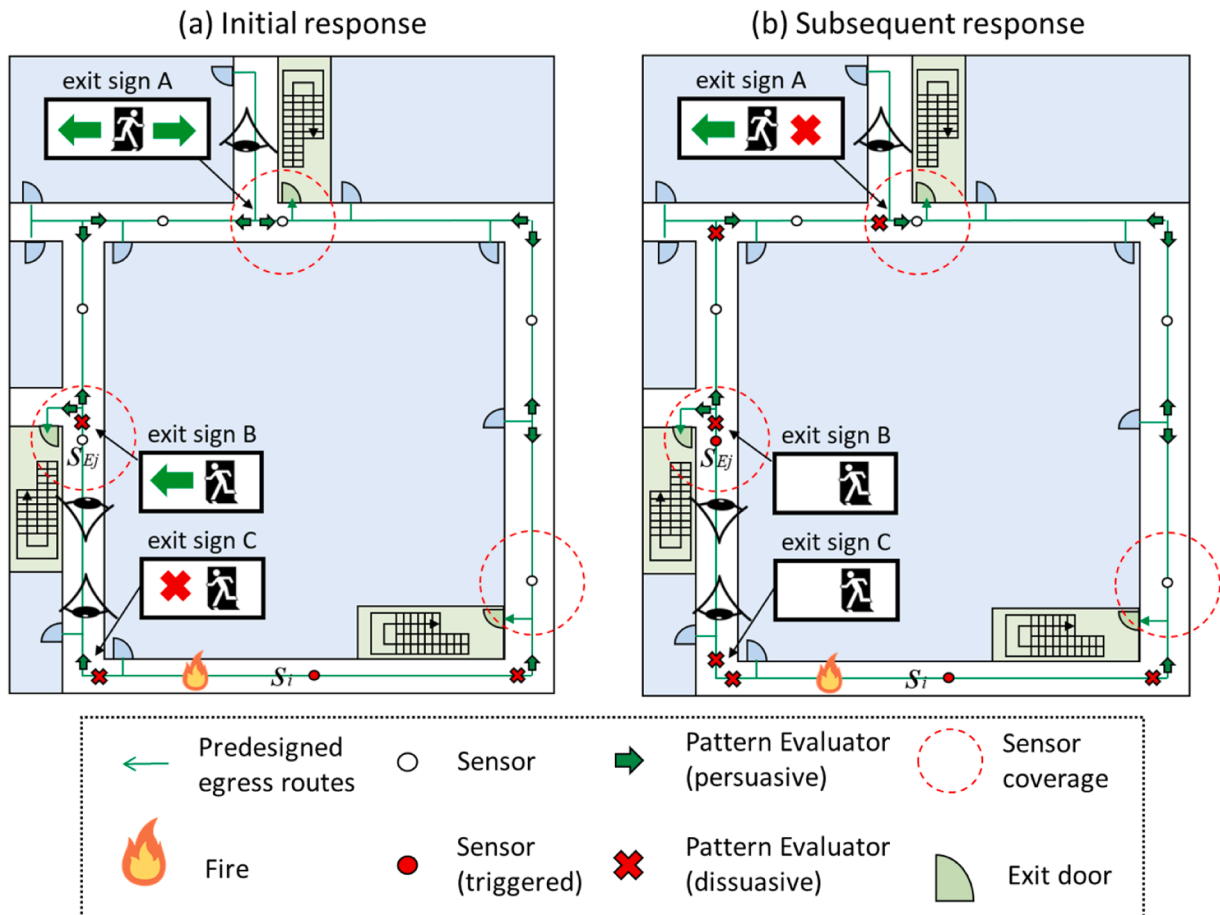


Fig. 5. An incident example of (a) the initial response where s_i is triggered, followed by (b) the subsequent response where s_{Ej} is triggered.

forward-looking, potential advancements and are not currently implemented in the existing setup. This advanced approach cross-verifies and validates the guidance provided to occupants to ensure it remains accurate and effective.

2.3. Dynamic exit sign network

The dynamic exit sign network is a critical response mechanism with the IDES, activated upon hazard detection. There are two operation modes of dynamic exit signs:

- 1) **Static Mode:** The exit signs operate as traditional signs and are denoted as D_0 .
- 2) **Dynamic Mode:** The exit signs display dynamic patterns and are denoted as D_1 .

The transition from D_0 to D_1 occurs when the Sensor Network is in emergency mode. In D_0 , the signs display only one pattern – Traditional Pattern (P_t), which is static and looks identical to traditional signs. In D_1 , the signs utilize two pattern types:

- 1) **Persuasive Pattern (P_p):** Aims to attract and direct evacuees towards safe routes with a dynamic feature.
- 2) **Dissuasive Pattern (P_d):** Aims to deter movement towards hazardous zones and minimize danger exposure with a dynamic feature.

Pattern Evaluators (PEs) are utilized to define these patterns. PEs are virtual entities assigned to exit signs' locations within the IDES layout before the hardware installation, which show all possible evacuation routes at one location. A case example is shown in Fig. 5, which illustrates the status of PEs on a map with the development of a fire. Let PE_i be the PE at the i^{th} sign location, connected to all potential exits via predefined evacuation routes. The function $f(PE_i)$ determines the pattern displayed by PE_i based on sensor inputs as

$$f(PE_i) = \begin{cases} P_p, & \text{if exit is reachable from } PE_i \\ P_d, & \text{if no exit is reachable from } PE_i \end{cases} \quad (2)$$

Fig. 5 illustrates the interaction between sensor activation, exit reachability, and the reversion mechanism in the IDES system. Sensor activation along a route affects the reachability status of an exit. If a sensor at position i (denoted as s_i) is triggered (see exit sign C upon the activation of s_i in Fig. 5(a) as the process of sensor-triggered updates to exit reachability is depicted), it sets the exit status linked via PE_i to unreachable. This ensures that occupants are dynamically redirected to alternative, safer evacuation routes. This function, reflecting this process by updating the status of an exit based on real-time sensor trigger, is presented as

$$\text{Reachability}(PE_i, \text{Exit}_k) = \begin{cases} 0, & \text{if } s_i \text{ is triggered} \\ 1, & \text{otherwise} \end{cases} \quad (3)$$

2.4. Mechanism of reversion to static signs

The system also includes a **reversion mechanism** to revert the exit sign from D_1 to D_0 under specific conditions, and in Fig. 5(b), the reversion mechanism of the IDES system is demonstrated. This mechanism operates when all Pattern Evaluators (PEs) at a specific location indicate P_d (indicating the presence of smoke or heat) or are under the coverage of a triggered sensor. Under these conditions, the system reverts the dynamic exit signs D_1 at that location to static exit signs D_0 that display pre-defined routes. If all PEs at a given location display P_d , or they are within the coverage of a sensor, the sign at that location also reverts to D_0 , which shows P_t only (see exit sign C and exit sign B upon the activation of an Exit Sensor s_{Ej} in Fig. 5(b) respectively). This is expressed by the inhibitory function $g(PE)$ as

$$g(PE) = \begin{cases} D_0, & \text{if all } PE_i \text{ at a location are } P_d \text{ or covered by a triggered sensor} \\ D_1, & \text{otherwise} \end{cases} \quad (4)$$

The primary aim of the **reversion mechanism** is to minimize errors during smoke and fire incidents, ensuring that escape route recommendations remain reliable. In real fire scenarios, the density and behavior of smoke can vary significantly based on factors such as the stage of fire development, the source of the fire, and the building's structural design [34]. This variability means that smoke characteristics differ with each fire incident. On the other hand, their influence on occupants is highly dynamic and spatiotemporal-specific.

In situations where smoke covers a specific area, it generally indicates that the fire has been developing for some time due to the extensive coverage. If dynamic exit signs are located within a smoke-filled region, they would be surrounded by smoke from all directions. Although the system might identify the fire origin over time and potentially guide occupants away from it, it is ethically problematic to direct them to pass through a smoke-dense area to reach an exit [12]. Even if this route might offer a higher chance of survival, an ethical dilemma arises. This is because instructing people to move through hazardous conditions can be seen as irresponsible.

Traditional exit signs, which have been in use for many years, are widely accepted by the public because they represent a standard, recognized safety measure [35–38]. In contrast, instructing occupants to navigate through smoke could be perceived as unsafe or unethical despite the potential for a safer outcome. This is where the **reversion mechanism** in the IDES becomes crucial. It allows the system to revert to a more conventional and ethically accepted method of directing traffic during specific conditions, such as the above-mentioned. This mechanism not only helps avoid ethical issues but also aligns with public expectations and accepted safety practices.

2.5. Design rules and control logic flow

Specific design criteria must be adhered to ensure the effectiveness of the IDES. The following design rules are established:

- (1) Sensors must, at a minimum, detect smoke; optimally, they should combine capabilities to monitor real-time temperature and smoke levels.
- (2) At least one sensor should be positioned between two adjacent dynamic exit signs along the evacuation routes.
- (3) At least one sensor, the Exit Sensor (s_E), must be installed near each exit door within its coverage. Its activation inhibits the egress route within its coverage.
- (4) If a dynamic exit sign cannot direct traffic toward a safe exit via the designated evacuation route, it must display a dissuasive pattern (P_d) in that direction.
- (5) A dynamic exit sign activates the **reversion mechanism** when all its associated Pattern Evaluators (PEs) indicate dissuasive patterns (P_d).
- (6) A dynamic exit sign activates the **reversion mechanism** when it is covered by any activated sensor.

Upon successfully implementing these design rules, the operational logic of the dynamic exit signs' pattern determination is summarised in Fig. 6. This figure distinguishes between 'normal scenarios,' where safe egress routes are identified, and 'special scenarios,' where no certain safe egress routes are discernible, potentially raising ethical concerns that might lead to increased panic or unsafe decisions by the evacuees if not managed correctly. For example, if an exit sign directs people towards an unexpectedly unsafe route, this could jeopardize their safety, raising serious ethical questions about the responsibility and reliability of the evacuation guidance system. This study proposes the reversion

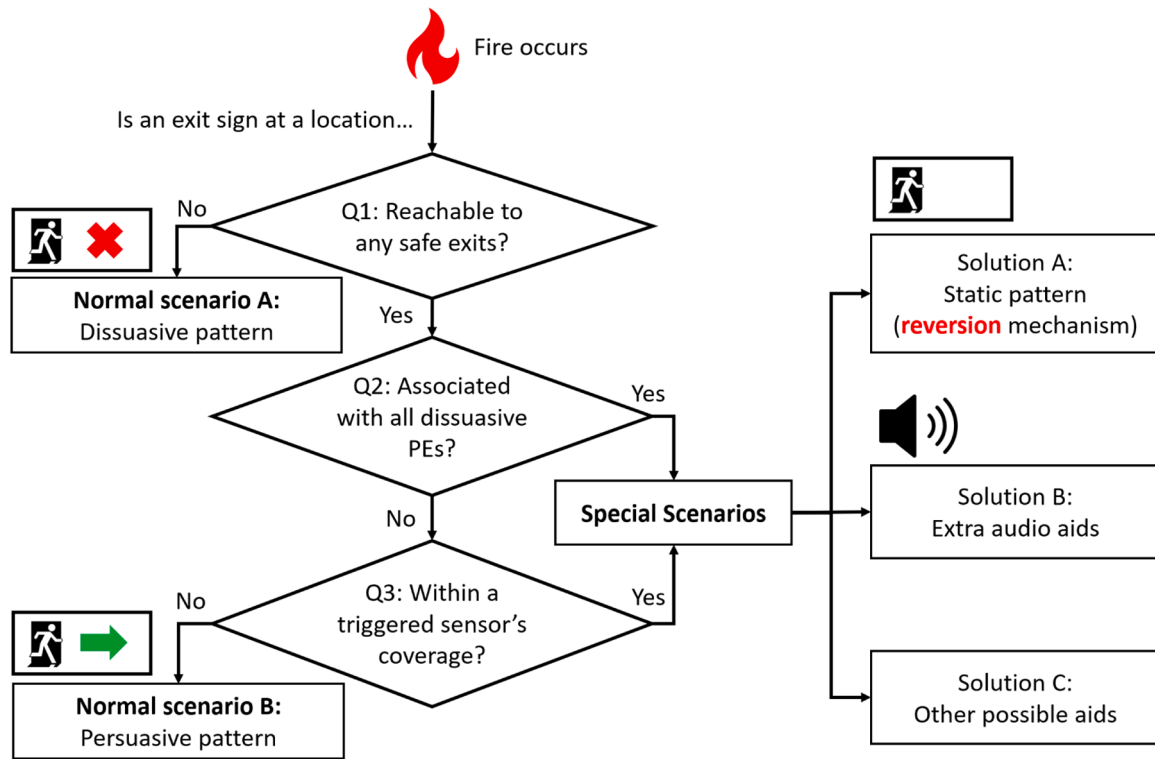


Fig. 6. The operational logic of the dynamic exit signs' pattern determination.

mechanism to minimize ethical and moral issues and suggests additional solutions, such as some extra audio aids from the Public Address (PA) system or other systems. To the best of the author's knowledge, the reversion mechanism is the simplest method to address ethical concerns effectively.

3. Tunnel demonstration

The tunnel demonstration is conducted due to its simpler structural configuration, allowing for a clear and straightforward evaluation of the IDES system's fundamental functionalities before extending the study to more complex environments. This experimental design focuses on validating the reliability of the sensors and the adaptability of the algorithm, which form the core of the IDES system. By using a controlled tunnel model, we can systematically assess the system's ability to dynamically guide occupants based on real-time hazard detection while minimizing potential interference from overly complex structural variables. This approach ensures that the foundational elements of the system, such as sensor accuracy, data processing efficiency, and algorithm responsiveness, are robust and effective.

3.1. Experimental set-up

The structure of IDES is demonstrated in the form of an Internet of Things (IoT) network within a scaled-down setup (see Fig. 7). This IoT network comprises hardware elements, including thermocouples, a data logger, computers, and microcontrollers within each dynamic exit sign. Considering the challenges of fire evacuation in the tunnel [39], we test the IDES system in a reduce-scale tunnel model (1:50) with dimensions of 1700 mm in length, 170 mm in width, and 140 mm in height. Four thermocouples are installed at the ceiling, each positioned between two adjacent dynamic exit signs. Three dual-directional dynamic exit signs, each integrated with an ESP32 model microcontroller unit (MCU), are installed at predefined positions to indicate the direction toward safe exits. The hardware communicates via the Message Queuing Telemetry

Transport (MQTT) protocol, allowing the real-time and efficient updating of the dynamic exit signs in response to the changing conditions within the lab-scale tunnel.

The tunnel dimension and the hardware positioning took references from the industrial cases; the separation of exit signs and exit doors in this tunnel simulates a full-scale road tunnel with exit doors separation of 100 m [40] and exit signs separation of 25 m [41]. Between every two neighboring exit doors, four exit signs are installed. Note that this experimental setup represents only a segment of a larger tunnel system. While only one exit is visible in the scaled model, the experimental design inherently assumes the presence of additional exits at either end of the tunnel, as would be typical in a complete tunnel scenario. Fig. 7(b) illustrates how the tunnel demonstration setup correlates with these real-world configurations.

A complete code has been developed, particularly for this tunnel demonstration. This code fulfils all criteria stated in *Design rules*. Thermocouples are used instead of smoke sensors in this study due to the hardware limitation of procuring the scale-down smoke detectors. Despite the procurement limitation, thermocouples represent fixed-point heat detectors on a real-life scale; they provide instant temperature readings that typical smoke sensors with only on/ off signals cannot provide. This approach also broadens future research possibilities by aiding in understanding more complex systems in tunnel infrastructure, such as the Linear Heat Detection (LHD) systems [42,43].

The temperature threshold for the thermocouples' readings in this study is set at 58 °C, a common set point for electrically connected heat detectors [44]. In this setup, thermocouples are used instead of smoke sensors. As no manufacturers specify the thermocouple's coverage area, this study assumed a 200 mm radius coverage of each thermocouple based on the heat sensor coverage from industrial standards [45] with the scaled-down method.

3.2. Experimental procedure

The experimental setup initiates a controlled fire within the tunnel to

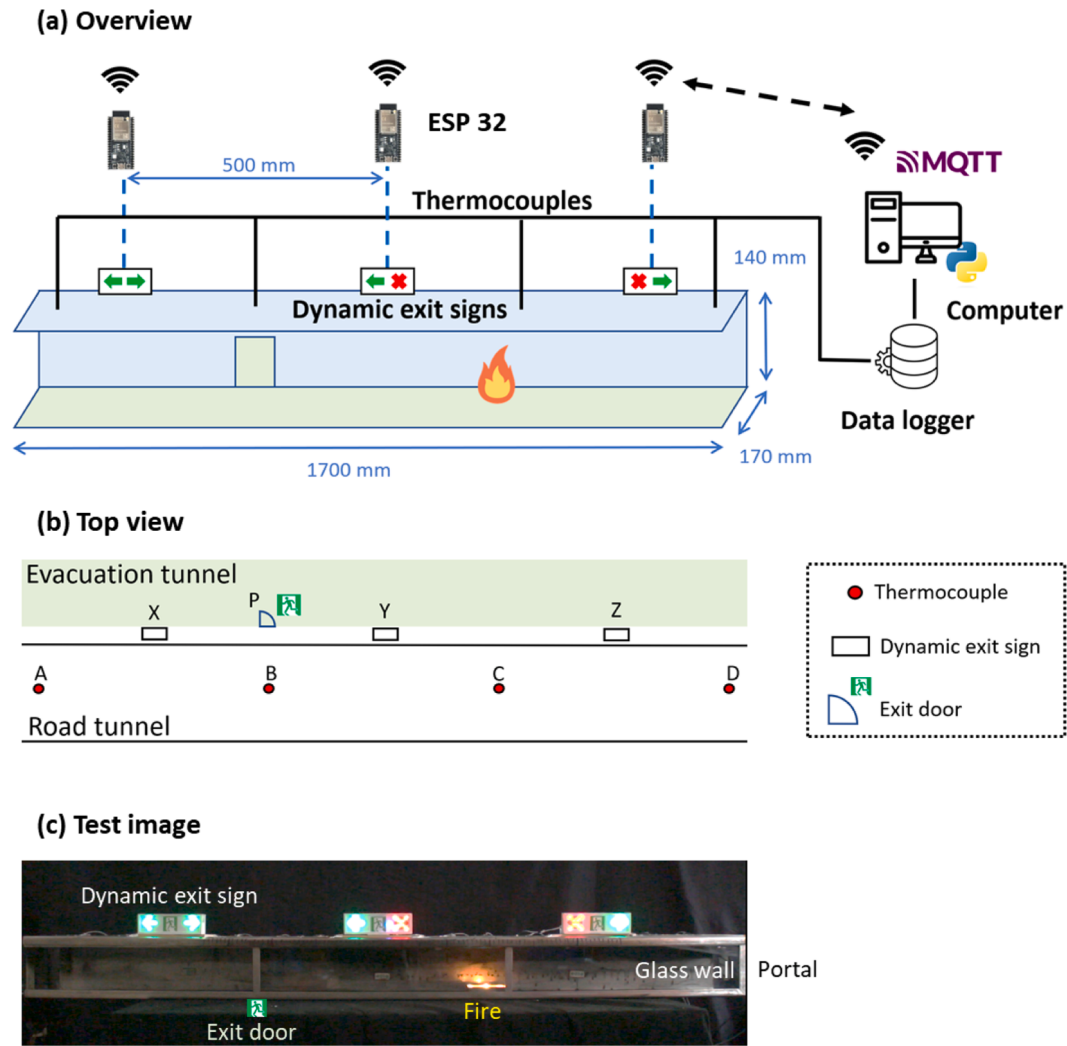


Fig. 7. (a) The systematic overview of the scaled tunnel, (b) the correlation of the tunnel with the real-world configurations, and (c) the illustration of the scaled tunnel.

evaluate the IDES's performance. To accurately simulate real-life fire scenarios on a smaller scale, the Heat Release Rate (HRR), alongside the fire's dimensions and location, are critical parameters in this study. Considering those parameters, Froude-number scaling analysis is employed [46]. This scaling method is widely used in fire safety engineering to model fire dynamics accurately while maintaining the physical properties of the fire at a reduced scale. The scaling is governed by the following equation:

$$\frac{Q_m}{Q_f} = \left(\frac{l_m}{l_f}\right)^{\frac{5}{2}} \quad (5)$$

where Q is the HRR, l is the length scale, and the subscripts "m" and "f" represent the model and full scales, respectively. By calculation, paraffin wax candles are chosen as the combustible material for the fire, which has an HRR of 41.28 ± 1.1 MJ/kg [47].

- **Fire HRR:** The HRR or power of fire is a critical metric for determining fire severity in incidents involving road tunnel fires. The HRR magnitude can vary widely, primarily depending on the vehicle types [48]. According to research, the peak HRR in a typical road tunnel fire can vary from 1.7 to 4.6 MW for passenger cars to 29–35 MW for single-deck buses [49–51]. However, since dynamic exit sign systems are designed for early detection and evacuation execution, thus common HRRs at 4 min since ignition in tunnel conditions are

considered, which is about 1.7 MW for passenger cars and 6 MW for buses [52]. This study simulates two types of fire sources that represent passenger cars and buses. The corresponding HRR for these fire sources is calculated using the scaled-down HRR method based on Froude-number scaling analysis.

- **Burning area:** This parameter is important to identify the coverage of fire source in a tunnel fire. Reasonably, the length and width of vehicles in road tunnel fire represent the fire dimension. As passenger cars and buses are simulated in the tunnel demonstration, the fire dimension shall also match the dimension of vehicles. In real life, the common size of a passenger car ranges from 4.3 m to 4.8 m (length) and from 1.7 m to 1.9 m (width) [53]; the average dimension of a single-deck bus ranges from 9.7 m to 20 m (length) and 3 m to 3.8 m (width) [54–57]. The dimension is also scaled down based on

Table 1

Comparison of the conditions of the study with real-life scenarios.

	Passenger Car Fire		Bus Fire	
	1:50 scaled test	Full-scale scenario	1:50 scaled test	Real-life scenario
Fire HRR	0.084 kW	1.5 MW	0.28 kW	5.0 MW
Burning length, width	90 mm, 40 mm	4.5 m, 2.0 m	200 mm, 50 mm	10.0 m, 2.5 m

Froude-number scaling analysis. Table 1 compares the conditions of this scaled-down study with real-life scenarios.

Five tests of experiments are divided into two groups to demonstrate the modes in *Dynamic exit sign network*: The first group is the normal scenario, depicting the typical behaviour of dynamic exit signs under standard conditions. The second group addresses special scenarios, highlighting the behaviour of dynamic exit signs in situations where safe egress routes are not clearly defined. The conditions of the five tests and the predicted patterns on all exits are listed in Table 2.

In the first group, Tests 1A and 1C are performed using a passenger car fire located at two different positions (i.e., near thermocouples A and C), as illustrated in Fig. 8. The centre of the fire source is located under the thermocouple. The objective of this group is to observe the accuracy and responsiveness of the change of dissuasive patterns on each exit sign.

The second group is the special scenario, where the entire thermocouple network is shifted 100 mm to the left, making thermocouple B an s_E of exit door P with exit sign X inside its coverage. Test 2B is performed using a passenger car; it simulates the exit sign X inhibition when s_E is triggered by the fire source with each centre located under thermocouple B (see Fig. 9(a)). Test 2D and Test 2D-b are a set of comparative demonstrations using two types of fire to simulate the exit sign Z inhibition when all its PEs show dissuasive patterns. The centre of the fire source is located under thermocouple D (see Fig. 9(b) and (c)).

3.3. Performance and demonstration of IDES system

Before presenting the details of the individual tests conducted, it is important to highlight that data is collected at one-second intervals. This frequency was selected as it offers a balance between data precision and volume, suitable for the objectives of the IDES demonstration. Thus, it ensures that the system's responsiveness and the effective activation of dynamic exit signs are accurately captured without the need for recording at fractions of a second. Additionally, all tests were documented using video recording, which has been accelerated threefold and supplemented with a timer to clearly indicate the timing of various incidents. This visual aid is available for reference (see Supplementary Videos).

In Test 1A (see Fig. 10(a)), a passenger car fire source started at thermocouple A at $t = 0$ s. The read temperature of thermocouple A exceeded 58°C at $t = 7$ s, and all dynamic exit signs react instantly. The fire was at the left of exit X, with only thermocouple A triggered, which did not block the evacuation path from the three exit signs to exit door P. Thus, exit signs X, Y and Z displayed a persuasive pattern to the direction of exit door P. For exit signs Y and Z, they displayed both persuasive patterns to the right, as the path was not blocked by any triggered

thermocouples.

In Test 1C (see Fig. 10(b)), a passenger car fire source started at thermocouple C at $t = 0$ s. The read temperature of thermocouple C exceeded 58°C at $t = 6$ s, and all dynamic exit signs reacted instantly. The fire was in the middle between exit signs Y and Z, with only thermocouple C triggered, which blocked the evacuation path from exit Z to exit door P. Thus, exit sign Z displayed a dissuasive pattern to the left and a persuasive pattern to the right. Exit signs X and Y had clear evacuation paths to exit door P, so they displayed persuasive patterns to exit door P. Exit sign X had a safe path to the left, thus showing a persuasive pattern, while exit sign Y had a dangerous path to the right, thus showing a dissuasive pattern.

In Test 2B (see Fig. 11(a)), a passenger car fire source started at thermocouple B at $t = 0$ s. The read temperature of thermocouple B exceeded 58°C at $t = 9$ s, and all dynamic exit signs reacted instantly. As thermocouple B is the s_E of exit P and covers exit sign X, its trigger inhibited exit sign X. For exit signs Y and Z, because the path to exit door P was blocked by triggered thermocouple B and the path to their right remained safe, so they displayed dissuasive patterns to the left and persuasive patterns to the right.

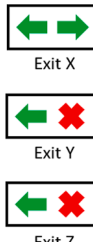
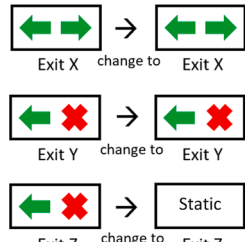
In Test 2D (see Fig. 11(b)), a passenger car fire source started at thermocouple D at $t = 0$ s. The read temperature of thermocouple D exceeded 58°C at $t = 6$ s, and all dynamic exit signs reacted instantly. The fire occurred at the right of exit sign Z. Three exit signs displayed persuasive patterns to exit door P. Exit sign X displayed a persuasive pattern to the left. Exit signs Y and Z displayed dissuasive patterns to the right.

In Test 2D-b (see Fig. 11(c)), a bus car fire source started at thermocouple D at $t = 0$ s. The read temperature of thermocouple D exceeded 58°C at $t = 3$ s, and all dynamic exit signs reacted instantly. The setup is identical to Test 2D, except the fire load increased. From $t = 3$ s to $t = 24$ s, the pattern response of the three exit signs was the same in Test 2D. At $t = 25$ s, the read temperature of thermocouple C exceeded 58°C , too, due to the accumulation of hot air at the tunnel's ceiling. Therefore, all PEs pointing left and right on exit sign Z displayed both dissuasive patterns. This inhibited exit sign Z at $t = 25$ s. The display patterns of exits X and Y remained unchanged.

The results are summarised in Table 3. Several observations are made:

- 1) **Responsiveness:** The latency for the exit signs to change patterns following a triggering condition was <0.1 second, demonstrating an immediate response when any thermocouple exceeded the 58°C threshold. This rapid responsiveness indicates that, given the high accuracy of the sensor network, the dynamic exit sign system performs satisfactorily at the laboratory scale.

Table 2
The scenarios of the five tests.

	Group 1: Normal scenario		Group 2: Special scenario		
	Test 1A	Test 1C	Test 2B	Test 2D	Test 2D-b
Fire location	Near A	Near C	Near B	Near D	Near D
Vehicle fire	Sedan	Sedan	Sedan	Sedan	Bus
Predicted sign patterns					

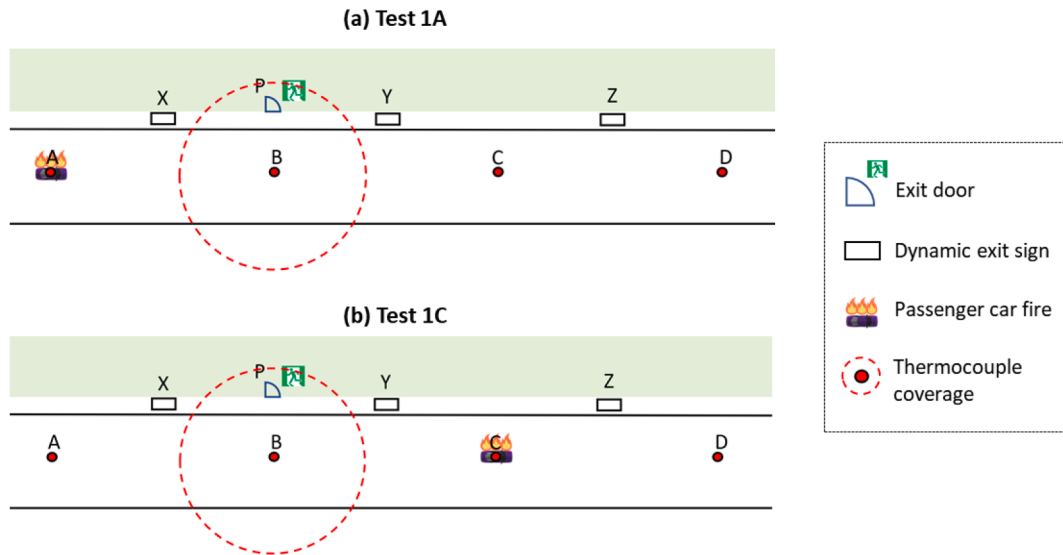


Fig. 8. Normal scenario demonstration set-up of (a) Test 1A – passenger car fire near thermocouple A, and (b) Test 1C – passenger car fire near thermocouple C.

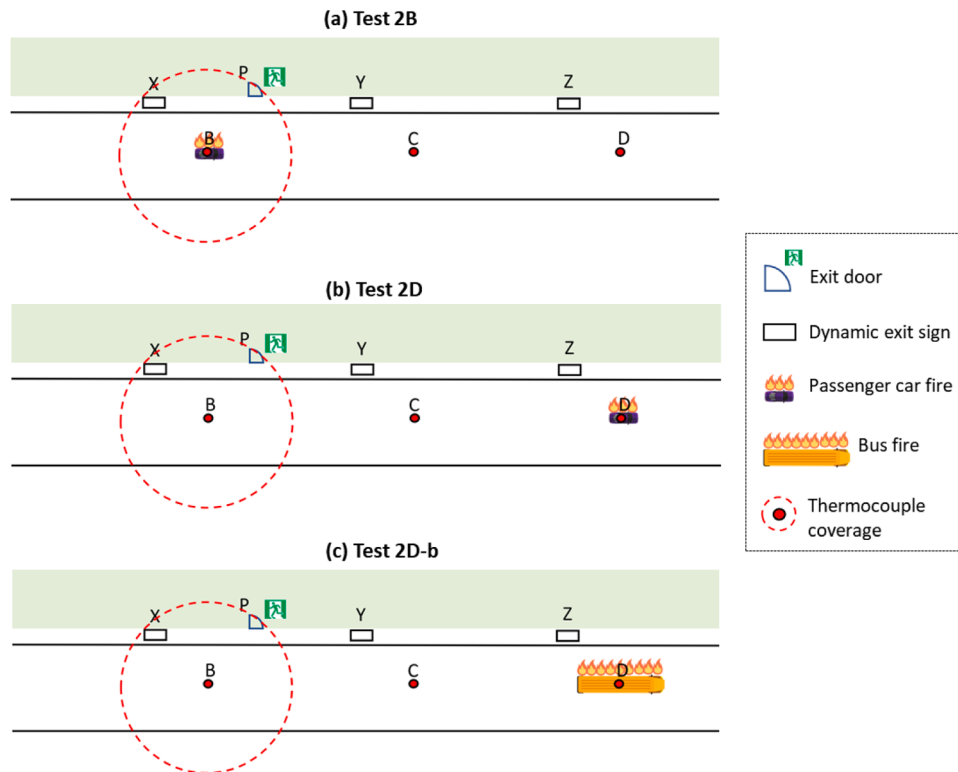


Fig. 9. Special scenario demonstration set-up of (a) Test 2B – passenger car fire near thermocouple B, (b) Test 2D – passenger car fire near thermocouple D, and (c) Test 2D-b – bus fire near thermocouple D.

- 2) **Accuracy:** The patterns displayed on the exit signs were consistently correct and displayed without errors. All exit signs changed patterns simultaneously and seamlessly, indicating robust synchronisation and error-free operation throughout the tests.
- 3) **Reversion Mechanism:** In this lab-scale tunnel setup, hot air accumulated at the ceiling over time, activating the reversion mechanism effectively. It is noted that in real-world scenarios, smoke propagation might occur faster than the spread of hot air. The reversion mechanism performed successfully in Test 2D-b, suggesting its potential effectiveness. To further validate the influence of smoke,

conducting a similar experiment at a full scale could be beneficial in future studies.

4. Discussion

4.1. Existing key challenges

While this study provides a foundational framework and guidelines, supported by experimental demonstrations, the transition of a dynamic exit sign system into a fully operational IDES for industrial-scale

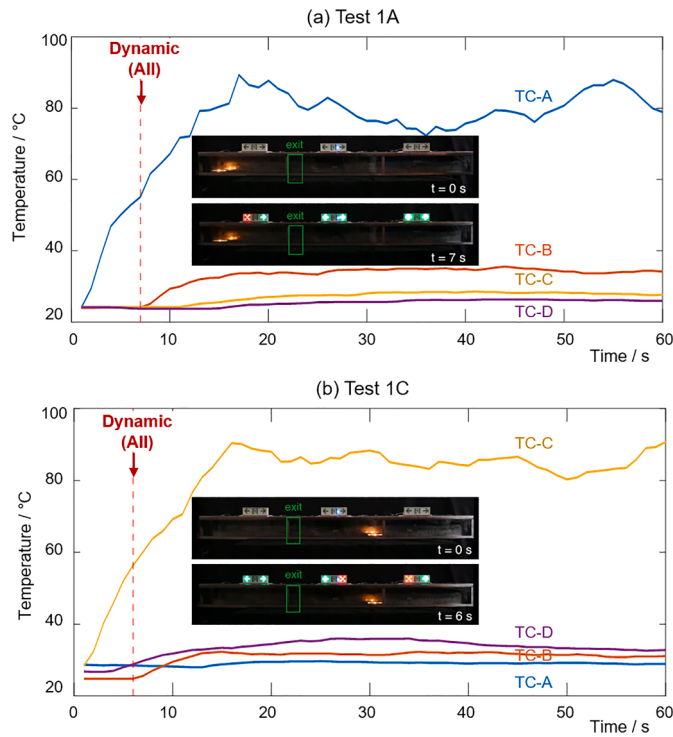


Fig. 10. Demonstration of normal fire scenarios, (a) Test 1A and (b) Test 1C (see Videos S1-S2).

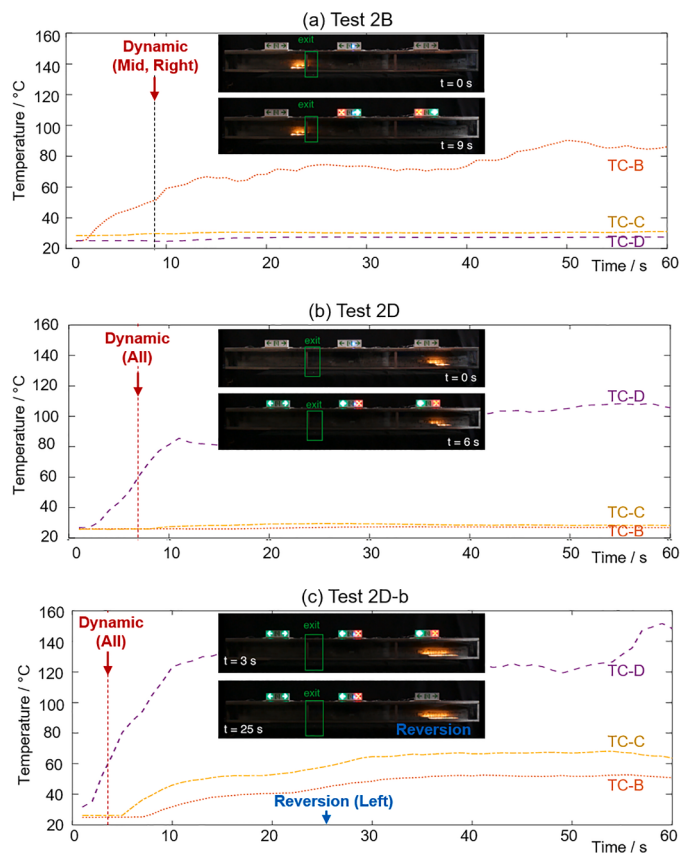


Fig. 11. Demonstration of special fire scenarios, (a) Test 2B, (b) Test 2D, and (c) Test 2D-b (see Videos S3-S5).

Table 3

The comparison of the results of the five tests.

	Group 1: Normal scenario		Group 2: Special scenario		
	Test 1A	Test 1C	Test 2B	Test 2D	Test 2D-b
Fire location	A	C	B	D	D
Burning vehicle	Sedan	Sedan	Sedan	Sedan	Bus
Responsive start time	7 s	6 s	9 s	6 s	3 s
Reversion start time	/	/	0s	/	25s

applications and real-life deployment encompasses numerous critical and technical focus areas. Each of these areas presents unique challenges and requires tailored solutions:

- 1) **Real-time data processing:** IDES is designed to efficiently process data in real-time, a critical requirement during emergency scenarios where multiple sensors may transmit data simultaneously. The main challenges in this context include handling potential data delays and managing a significant influx of data without performance degradation. Additionally, mitigating signal interference is essential to maintain the reliability and scalability of the system for broader, real-world applications. Note that in a harsh fire environment, abrupt signal breakdown might occur due to high heat and dense smoke [58]. One promising solution to these challenges is the implementation of edge computing. This technology represents a significant advancement in real-time data processing by enabling data to be processed locally at the source, drastically reducing latency and enhancing emergency systems' responsiveness. Recent developments have equipped edge devices with increased computational power, allowing them to handle complex computations and run sophisticated algorithms independently. However, deploying edge computing also presents its own set of challenges, including energy and Quality of Service (QoS) constraints [59]. Additionally, standardising performance across diverse edge devices is a sophisticated task to ensure consistent and reliable system operation [60].
- 2) **Hardware placement:** Effective implementation of IDES hinges on optimal hardware placement, as stipulated in *Design rules*. The physical layout of exit signs and evacuation routes typically falls under the purview of architects and building engineers; however, the strategic placement and the number of sensors require meticulous planning. Recent advancements in wireless communication protocols, such as Wi-Fi 6, LoRaWAN, or Bluetooth Low Energy (BLE), are pivotal in addressing these challenges. For instance, LoRaWAN, highlighted for its long-range and low-power capabilities, can be particularly effective in extensive environments like tunnels where sensors might be widely spaced [61]. Similarly, selecting appropriate technologies like Wi-Fi or BLE based on the specific requirements for localisation accuracy and power efficiency ensures the IDES system operates reliably and efficiently [62].
- 3) **Multi-fire scenarios:** Standard industry practices often assume a single fire source when developing safety protocols, as this simplifies the analysis and design of evacuation strategies. Similarly, the IDES is initially designed with this assumption, which thus may not suffice in complex scenarios involving multiple fire sources. In future development, the IDES could be integrated with other building management systems, such as HVAC (Heating, Ventilation, and Air Conditioning) and fire suppression systems, to create a cohesive response strategy for multiple fire sources. For instance, in the event of multiple fires, the IDES could work in conjunction with ventilation systems to control smoke spread. Simultaneously, the dynamic exit sign network could adapt in real-time, guiding evacuees along the most secure paths based on updated hazard and environmental data. This integration would not only enhance situational awareness but

also improve the overall efficiency and safety of evacuation procedures in highly complex scenarios.

4) **Infrastructure types:** The deployment of IDES across various infrastructure types presents several unique challenges. In road tunnels, environmental conditions such as high humidity, concentrated airborne particulates and substantial vehicular emissions can severely compromise sensor integrity [63]. Consequently, it is essential to enhance the sensitivity and incorporate additional protective layers for sensors in these settings. In industrial buildings, electromagnetic interference poses a significant threat to system reliability [64], necessitating the implementation of robust shielding and the use of advanced network protocols within IDES to ensure stable wireless communication. Furthermore, high-rise buildings, characterised by the presence of obstructive materials, may impede network connectivity [65], requiring the integration of signal amplification technologies or the adoption of more penetrative communication standards to maintain system efficacy.

4.2. Coupling with artificial intelligence

The future integration of artificial intelligence (AI) is imperative to elevating the capabilities of the IDES system. AI technologies transform IDES into a comprehensive smart fire protection system on different levels (see Fig. 12). AI technologies enable IDES not only to respond to existing conditions but also to anticipate future scenarios.

Level 1 – Predictive Analytics and Machine Learning: The core of the IDES utilizes predictive analytics and machine learning to interpret data from environmental sensors monitoring aspects such as temperature and smoke concentration. For this purpose, machine learning models such as Random Forests or Support Vector Machines (SVMs) are employed due to their proficiency in handling regression and classification tasks, which are crucial for predicting the behaviour and spread of fire based on historical and real-time sensor data [66,67]. These models analyse sensor outputs to forecast the development and movement of fire within the tunnel, enabling the system to issue early warnings and initiate pre-emptive evacuation measures [68,69]. This integration allows the system to identify potential hazards early and adapt evacuation strategies dynamically, preventing delays in occupant response. This predictive capability ensures that evacuations occur before conditions deteriorate to critical levels, thus maximizing safety and minimizing potential harm.

Level 2 – Deep Learning for Enhanced Decision Making: Deep learning significantly enhances the decision-making capabilities within IDES by utilizing neural networks to process data from integrated

cameras and sensors. Specifically, Convolutional Neural Networks (CNNs) analyze video feeds in real-time to detect smoke and fire signatures. Beyond identifying hazards, this system can monitor crowd density at exits. This dual functionality enables the system to assess both environmental hazards and human movement patterns, facilitating more informed evacuation decisions [70,71].

Additionally, Recurrent Neural Networks (RNNs), focusing on Long Short-Term Memory (LSTM) networks, play a vital role in analysing the sequential data of crowd movements. These networks utilize temporal data collected from cameras and sensors to identify patterns in crowd density and movement trends over time. By continually integrating new sensor inputs, LSTM networks are not just tracking current conditions but are actively predicting human flow dynamics. This predictive capability enables them to foresee potential congestion points and proactively [72–74]. This capability ensures that IDES adapts to both the physical environment and occupant behavior in real time, enhancing evacuation efficiency.

Together, these systems operate in concert to monitor the environment and respond to emerging threats or bottlenecks. This integration allows IDES to dynamically adjust exit sign directions, guiding occupants through safer, less crowded paths. The real-time image and sequential data processing ensures that the system adaptively enhances safety by redirecting flows based on the most current conditions. To validate the effectiveness and reliability of this integrated approach, extensive simulations and real-time drills along with VR and AR technology [73,74] will be conducted, testing the system’s responsiveness and accuracy under various emergency scenarios. These trials aim to identify potential limitations and refine the system for broader implementation.

Level 3 – Risk Assessment for Safer Evacuations: The most sophisticated AI application within IDES involves assessing the correlation between human exposure to fire-related hazards and the effectiveness of the evacuation process using Dynamic Bayesian Networks (DBNs). DBNs provide a probabilistic approach to model the dependencies and uncertainties associated with various risk factors like smoke inhalation, heat exposure, and proximity to hazards [75]. By dynamically updating risk assessments based on real-time data, DBNs enable the system to refine evacuation strategies continually, ensuring that routes remain both viable and safe. This method allows IDES to predict and continually update the risks associated with different fire scenarios and their impact on evacuation safety. With this knowledge, the system can adjust exit sign directions in real time to minimise human exposure to dangers, thereby ensuring that the chosen escape routes are the safest possible under both present and anticipated future conditions. These adjustments

AIoT-driven IDES System		IoT sensors			Architecture	Assessing factors	
Level of Intelligence							
Level 3 Risk Assessment for Safer Evacuations		✓	✓	✓	✓	✓	✓
Level 2 Deep Learning for Enhanced Decision Making		✓	✓	✓	✓		
Level 1 Predictive Analytics & Machine Learning		✓	✓				

Fig. 12. IDES future development coupling with Artificial Intelligence.

ensure a balance between evacuation speed, safety, and practicality, particularly in high-risk scenarios.

5. Conclusion

This study introduces a framework of the IDES system and tests its feasibility with a demonstration of a lab-scale tunnel model. The demonstration consists of five experiments, and the IDES consistently met its design objectives, affirming the efficacy of its operational principles under simulated conditions. Notably, the system demonstrated a remarkably short response time of just a few seconds, highlighting the potential to provide timely guidance during emergencies. Additionally, a reversion mechanism is introduced to address ethical and moral considerations in developing dynamic exit sign systems.

The experimental results underscore the superiority of dynamic exit signs over traditional signs, as they actively prevent evacuees from entering areas that pose imminent threats. It is emphasized that the design of dynamic exit sign systems should prioritize actively discouraging evacuees from approaching dangerous areas through strategic dissuasive signalling. Although reducing evacuation time is advantageous, it is imperative that this does not detract from the system's primary objective of maximizing evacuee safety.

Further research should explore implementing IDES on a real-life scale set-up and integrating more advanced AI technologies to predict evolving threats dynamically. The core objectives are potentially enhancing the system's effectiveness in real-world scenarios. Ultimately, the proposed IDES system represents a step forward in way-finding solutions during emergencies.

The implications of this research extend to enhancing safety protocols in infrastructure emergencies by providing dynamic navigational aid. The established design principles and operations of IDES lay significant groundwork for advancing the theoretical and practical understanding of dynamic exit sign systems, offering a foundational reference for subsequent research and development.

Ethics Statement

Not applicable because this work does not involve the use of animal or human subjects.

Data availability

Data will be made available on request.

CRediT authorship contribution statement

Ho Yin Wong: Writing – original draft. **Meng Wang:** Software, Investigation. **Xiaoning Zhang:** Formal analysis. **Yuxin Zhang:** Writing – review & editing, Formal analysis. **Ming Chi Wong:** Software, Resources, Data curation. **Xinyan Huang:** Writing – review & editing, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.jnlssr.2024.12.001](https://doi.org/10.1016/j.jnlssr.2024.12.001).

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