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Quantitative Simulation of Human Evacuation Dynamics under Visibility Impairment in Indoor Fire Scenarios

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Abstract

This study quantitatively analyzes the impact of visibility degradation caused by smoke spread on human evacuation behavior during indoor fires. Hence the reaction-based evacuation model outlined in the New Zealand Fire Safety Verification Method (C/VM2), simulations were conducted to observe how evacuees respond under conditions of gradually decreasing visibility due to increasing smoke concentration. Specific behavioral changes were examined, including Response Time, Route Selection, Avoidance Behavior, and Situational Awareness. For the purpose of this study, an indoor environment was modeled, and smoke spread was visualized to design an evacuation model that reflects visibility constraints. The analysis revealed that once smoke concentration exceeds a certain threshold, evacuees face significant visual impairment, leading to delay in evacuation and increased risk of collisions. Furthermore, the Presence of Smoke Control System, the Status of Door Opening, and the Configuration of Evacuation Route were found to be closely related to visibility during fire events. It emphasizes the importance of incorporating visibility-based strategies into evacuation planning alongside physical architectural considerations in performance-based fire safety design. It also suggests the potential for integrating psychological response factors and AI-based predictive systems in future research.

Keywords: *Smoke Propagation, Visibility Reduction, Evacuation Behavior Analysis, Fire Simulation.*

Introduction

Rapid urbanization has heightened the risk of fire incidents in multi-use facilities and other enclosed indoor spaces, thereby exacerbating the potential for loss of life [1]. In large buildings, shopping malls, subway stations, exhibition halls, and airport terminals, smoke spread often poses more critical threat than flames themselves. Recent statistics show that more than 60 % of fatalities in indoor fire stem from toxic-gas inhalation and evacuation delays caused by impaired visibility. As smoke concentration rises, occupants' visual range contracts sharply, leading to diminished decision-making capacity, reduced walking speed, and poorer route-finding ability, all of which critically undermine overall evacuation efficiency. Most existing fire-safety simulations analyze heat transfer, smoke propagation, and human egress behavior in isolation, or focus solely on the physical dispersion of smoke without incorporating cognitive factors such as visibility, fear, or confusion [2][3]. Empirical research on how visibility dynamics influence crowd behavior remains scarce; when considered at all, studies often assume single-exit layout or employ a static visibility threshold. In reality, smoke concentration varies non-linearly over both time and space, and this dynamic visibility change directly affects Route Selection, Collision Avoidance, and Crowd Congestion [4][5]. To address this gap, the present study applies the Reaction-Based Evacuation Model specified in the New Zealand Fire Safety Verification Method (C/VM2) to integrally examine evacuee responses under evolving visibility and toxic-gas conditions. C/VM2, an internationally recognized performance-based design tool, sets an evacuation initiation criterion at a line-of-sight distance below 10 m and employs the Fractional Effective Dose (FED) to quantitatively evaluate survivability and egress feasibility. These benchmarks provide a scientifically grounded basis for realistic evacuation assessment.

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Our approach integrates real-time visibility degradation data into the evacuation model, dynamically coupling smoke concentration, temperature, carbon-monoxide levels, and FED values with agent-based behavioral rules. It advances the field in three key respects:

(1) Implement a generalized indoor-space model that encompasses the entire facility rather than a single-exit domain.

(2) Generate quantitative, spatial-temporal data on visibility fluctuations induced by smoke spread.

(3) Construct a fully dynamic simulation framework that fuses visibility degradation with adaptive evacuation patterns.

This holistic methodology replicates real-world evacuation environments more faithfully than conventional static analyses and yields critical data for refining architectural design codes, developing smart evacuation guidance systems, and creating AI-driven emergency-response solutions. Beyond theoretical modeling, the proposed visibility-aware framework can be deployed in practical fire-safety operations and forms an essential component of smart-city and disaster-resilience technologies.

Related Works

Smoke Propagation and Visibility Degradation

Smoke is a critical factor that degrades the evacuation environment during fires, as it limits visibility and impairs the ability to identify escape routes, thereby affecting both Evacuation Speed and Path Selection. Studies have shown that when visibility drops below 10 meters, evacuation initiation is significantly delayed. At visibility levels below 5 meters, most evacuees struggle to identify exits, and when visibility falls below 2 meters, they often lose the ability to make pathfinding decisions, frequently entering a state of confusion or panic.

International standards such as NFPA 130 and ISO/TR 16738 adopt a visibility threshold of 10 meters as the criterion for safe evacuation, which is also reflected in the C/VM2 guidelines [6][7][8]. Simulations can model evacuee speed as a function of smoke concentration or visibility using the following equation:

$$v = v_0 \cdot \exp(-\alpha \cdot C) \quad (1)$$

In this formula, v represents the actual movement speed, v_0 is the base (unimpeded) walking speed, C denotes smoke concentration or inverse visibility, and α is a sensitivity coefficient representing the degree to which speed is affected by the smoke environment.

Toxic Gas Exposure and the FED Model

Toxic gases such as carbon monoxide (CO) and hydrogen cyanide (HCN), released during fires, have a direct impact on human survivability [9][10][11]. The Fractional Effective Dose (FED) model is commonly used to evaluate this impact, with a general formulation expressed as:

$$FED = \int_0^t \left(\frac{C_{CO}(t)}{Cref}\right) \mathrm{d}t \quad (2)$$

Here, $C_{CO}(t)$ represents the concentration of carbon monoxide at time t, and C_{ref} denotes the reference lethal concentration (typically 3500 ppm). When the FED value reaches 0.3 to 0.5, individuals may experience unconsciousness or cognitive impairment; at a value of 1.0, fatal outcomes are likely.

Analysis Procedure Based on Fire, Smoke Propagation, and Evacuation Scenarios

Construction of Fire and Smoke Propagation Model

The primary objective of this study is to quantitatively analyze the effects of visibility degradation caused by smoke propagation during indoor fires on evacuees' behavior and route selection. By incorporating real-time visibility reduction often overlooked in prior studies into evacuation behavior, it aims to more realistically simulate human responses in disaster scenarios. This contributes to the development of safer indoor architectural designs and more effective emergency evacuation plans.

It is composed of two main stages: a fire and smoke propagation simulation, and an evacuation behavior simulation. These simulations are interlinked and ultimately used to evaluate the quantitative impact of visibility degradation on evacuation speed and route decisions. The fire simulation utilizes the Fire Dynamics Simulator (FDS) engine, which performs three-dimensional calculations of complex heat transfer and smoke propagation phenomena. Parameters for fire growth and heat release rate are established in reference to the New Zealand Verification Method C/VM2. The fire growth characteristics are modeled using the following equation:

$$Q(t) = \alpha \cdot t^2 \quad (3)$$

Where $Q(t)$ represents the heat release rate (kW) at time t, α is the fire growth coefficient (0.04689 kW/s²), and t denotes time in seconds. The total simulation duration is set to 300 seconds, during which the development of the fire and associated smoke emission is realistically reproduced. The distribution of smoke concentration and temperature changes is visualized using Smoke view, and the data are used to calculate the reduction in visibility for evacuees.

Configuration of Evacuation Behavior Simulation and Experimental Scenarios

The evacuation simulation calculates individual evacuee positions, movement speeds, and route selections based on environmental conditions. Smoke concentration and visibility data extracted from the fire simulation are used to adjust evacuees' movement speeds via a velocity reduction coefficient. Visibility degradation, in particular, has a critical influence on walking speed. To reflect this, it refers to the visibility-speed correlation proposed by Gibson et al., where evacuee speed can decrease by up to 30% when visibility falls below 10 meters.

The experimental scenarios are designed to emulate realistic fire conditions in large underground shopping malls and multi-use facilities by constructing a virtual environment. The objective is to systematically observe behavioral changes in evacuees caused by visibility degradation due to smoke propagation.

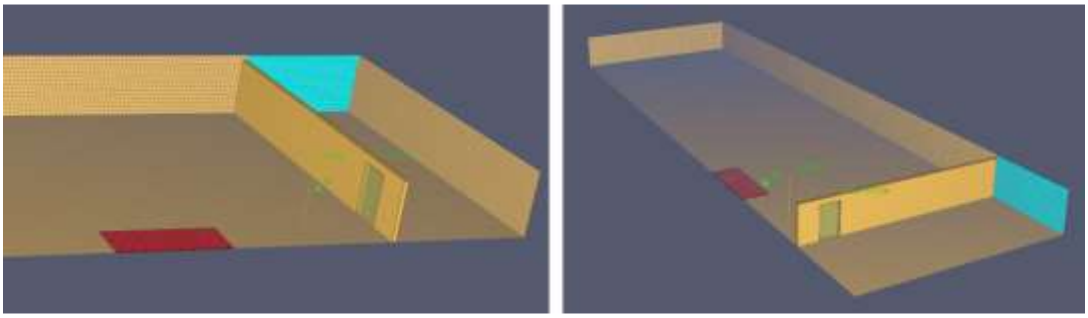


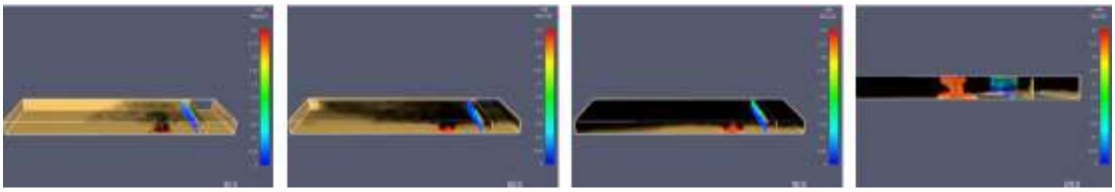
Fig. 1. Indoor Spatial Layout and Scenario Application

The modeled space includes walls, pillars, and display stands made of both fire-resistant and non-fire-resistant materials to assess their impact on heat conduction and smoke infiltration pathways. Natural and mechanical ventilation effects were minimized to isolate the pure influence of smoke propagation.

Table 1. Parameter Settings for Fire Scenario Simulation

Parameters	Details
Fire Growth Coefficient	0.04689 kW/s² (fast-growing fire)
Maximum Heat Release Rate	Set to 3.2 MW (fire grows over 300 seconds)
Fuel and Ignition Source	Considered based on the heat release characteristics of interior materials
Smoke Production Rate	Applied using parameters from the default FDS library
Total Simulation Time	300 seconds, with output data collected at 1-second intervals

The fire scenario assumes ignition caused by an electrical fault near the main entrance, applying parameters based on the New Zealand Verification Method (C/VM2), as presented in Table 1.

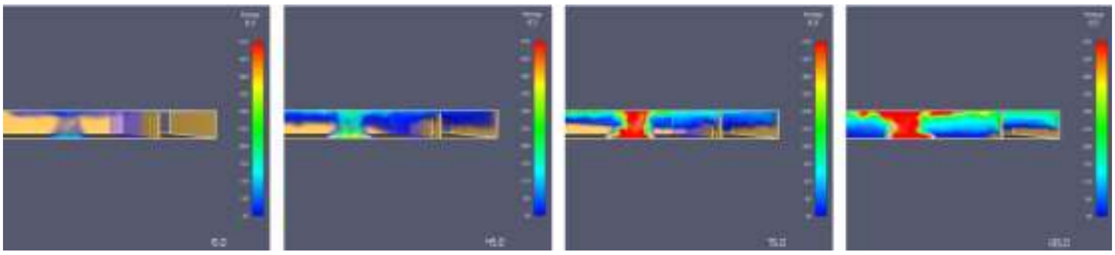


(a) 30 seconds (b) 60 seconds (c) 90 seconds (d) 120 seconds

Fig. 2. Illustrate the Progression of Smoke Spread Following Ignition over Time Intervals of (a) 30 seconds, (b) 60 seconds, (c) 90 seconds, and (d) 120 seconds.

The experimental environment was divided into two zones: Zone A, a large area with high population density, and Zone B, a smaller space connected to the exterior. Both zones were conceptualized as part of a multifunctional commercial facility. Zone A had a floor area of 644.179 m², and Zone B covered 93.282 m², both consisting of single-floor layouts with a ceiling height of 3 meters. The fire scenario was constructed under the assumption of ignition near the main entrance due to electrical malfunction. The connecting entrance between Zones A and B was modeled to be activated by a fire detection system. Prior to evaluating evacuees' visibility, a comprehensive analysis of the overall fire environment was conducted. As shown in Fig. 2, the time-series data visualizes the extent and rate of smoke dispersion over a total simulation duration of 300 seconds.

During the initial 30 seconds, smoke remained largely confined and showed upward movement toward the tallest vertical surfaces, posing minimal visibility impairment for evacuees. However, after 60 seconds, smoke propagation began to accelerate, rapidly filling Zone A and reaching the connecting entrance to Zone B. At 90 seconds, the smoke had engulfed nearly the entire area, though it had not yet descended to floor level at the entrance. In a real-world scenario, maintaining a low posture could still enable limited mobility; however, due to reduced oxygen concentration and increasing thermal conditions, evacuation would become significantly more difficult beyond this point.



(a) 15 seconds (b) 45 seconds (c) 75 seconds (d) 135 seconds

Fig. 3. Show The Temporal Spread of Heat After Ignition.

The thermal distribution became critically hazardous after approximately 75 seconds, and by 90 seconds, intense heat had expanded well beyond the ignition point, reaching levels incompatible with human tolerance.

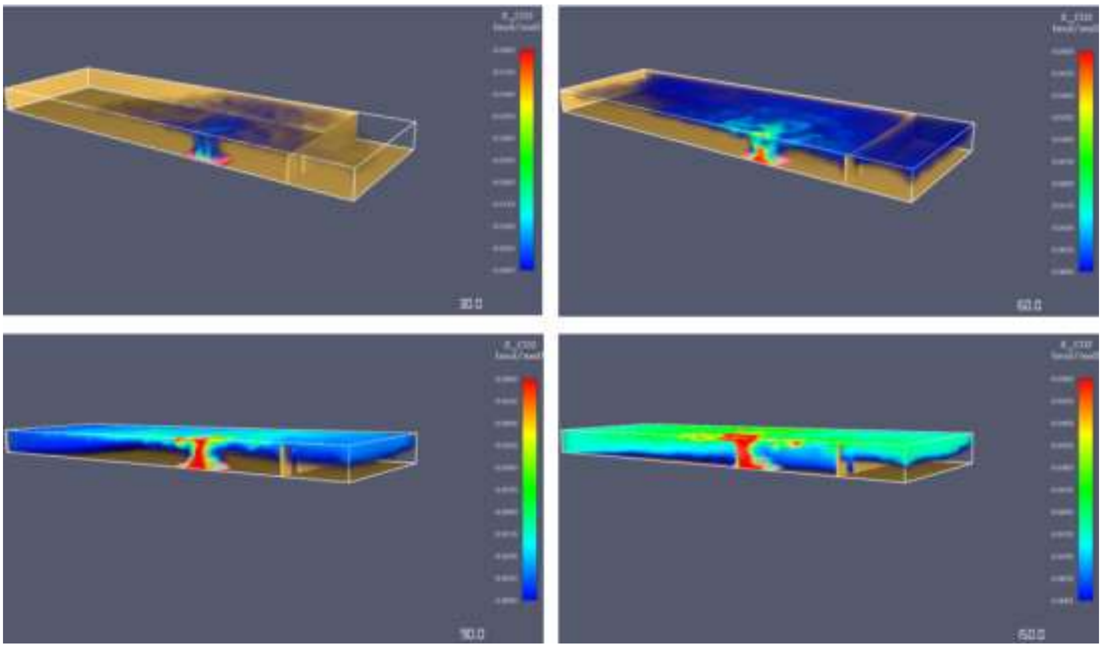


Fig. 4. Provide the Corresponding Spatial Distribution of CO_2Concentration during the Fire Progression.

Scenario Design for Human Visibility Experiment

The evacuation scenario involved 200 virtual agents, distributed uniformly across high-density commercial spaces and corridors. The average walking speed of agents was set at 1.2 m/s, with demographic variability (e.g., age and gender) accounted for in speed assignments. Visibility degradation zones were modeled to reduce walking speed by up to 30%, and the simulation activated mechanisms for collision avoidance and congestion buildup between agents. Each agent was initially programmed to evacuate through the nearest available exit. While some agents were allowed to reroute in response to increasing smoke density, the simulation environment was designed with a single final exit to isolate and analyze the impact of visibility degradation alone. As the evacuation software does not natively support speed reductions based on visibility, a customized indirect method was used. Smoke view output data specifically, smoke density and visibility maps were extracted and dynamically mapped to agent locations to compute individual speed adjustments.

The relationship between visibility (V) and walking speed was defined using the following degradation function:

$$v_{reduced} = v_{nominal} \times f(V) \qquad (4)$$

Where $f(V)$ is a piecewise function defined as:

$$f(V) = \begin{cases} 1, & V > 10m \\ 0.8, & 5m < V \leq 10m \\ 0.6, & 2m < V \leq 5m \\ 0.4, & V \leq 2m \end{cases} \qquad (5)$$

Table 2. Standardized Speed Reduction Factors Based on Visibility Ranges

Visibility Range (m)	Speed Reduction Factor ($f(V)$)	Visibility Level	Maximum Walking Speed
> 10 m	1,0	Normal Visibility	Normal: 1.3 m/s
5m ~ 10m	0.8	Moderate Visibility	Moderate: 1.0 m/s
2m ~ 5m	0.6	Low Visibility	Low: 0.8 m/s
≤ 2 m	0.4	Very Low Visibility	Very Low: 0.5 m/s

The experiment divided agents into four groups based on visibility range, including 50 agents in each group for a total of 200 agents. The visibility ranges were segmented, and each group was assigned a different walking speed corresponding to four visibility-based levels.

Experiment and Evaluation

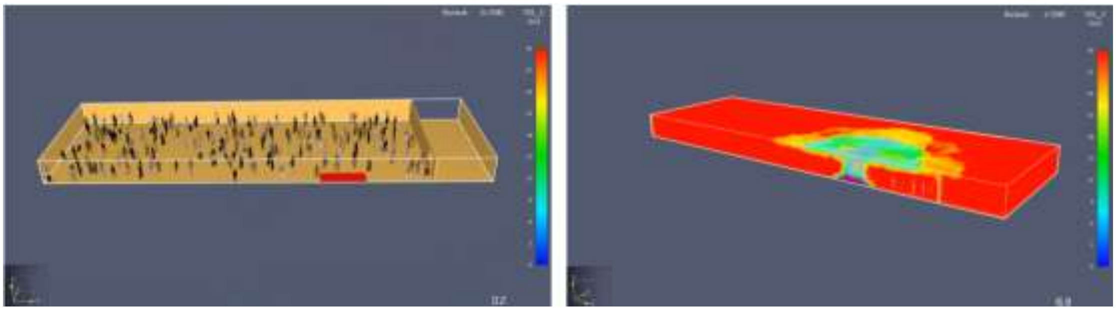
Indoor Structural Analysis of the Experimental Environment

The experimental scenario in this study was designed to reflect the spatial characteristics of actual multi-use facilities and the typical development of fire incidents as accurately as possible. The simulation space was modeled to facilitate visibility-related experiments, and the main structural elements were configured considering both fire-resistant and non-fire-resistant materials.

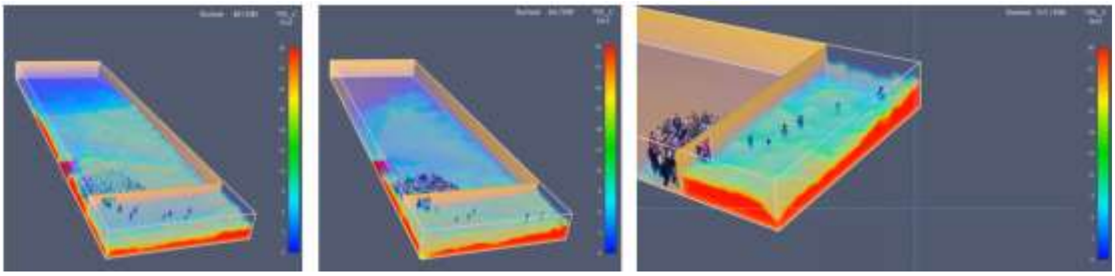
The fire source was assumed to originate near the entrance due to an electrical ignition, and the fire was set to develop over a 300-second period. From the moment of ignition, smoke rapidly spread, with the thermal flow and smoke concentration near the ceiling significantly affecting evacuation routes and evacuees' visibility. It spread out rapidly along the ceiling surface, and the scenario was designed so that the smoke concentration and temperature distribution near the entrance gradually increased. To reflect realistic evacuee behavior, 200 agents were simulated as evacuees. These agents had individual differences in initial positions, age, and walking speed, and to model speed reduction in low-visibility zones, the experiment divided them into four groups according to visibility levels.

Analysis of Experimental Results

According to the observed results of smoke propagation in this study, during the first 50 seconds after ignition, the smoke primarily remained within the ignition source area and the adjacent ceiling surface.



(a) Ignition (b) 15 seconds



(c) 90 seconds (d) 120 seconds (e) 200 seconds

Fig. 5. Present Visibility Snapshots at (a) Ignition, (b) 15 seconds, (c) 90 seconds, (d) 120 seconds and (e) 200 seconds.

During this period, the smoke concentration was low, and visibility remained above 15 meters, with no significant visibility reduction observed in the corridor or around the exit. However, as shown in the t^2 curve of the HRR (Heat Release Rate) in Fig. 7, the flames began to grow rapidly, and around 110 seconds, a hot layer near the ceiling started spreading toward the exit. By 135 seconds, a substantial smoke layer had formed.

(a) 30 seconds (b) 60 seconds (c) 150 seconds

Fig. 6. Smoke Diffusion over Time.

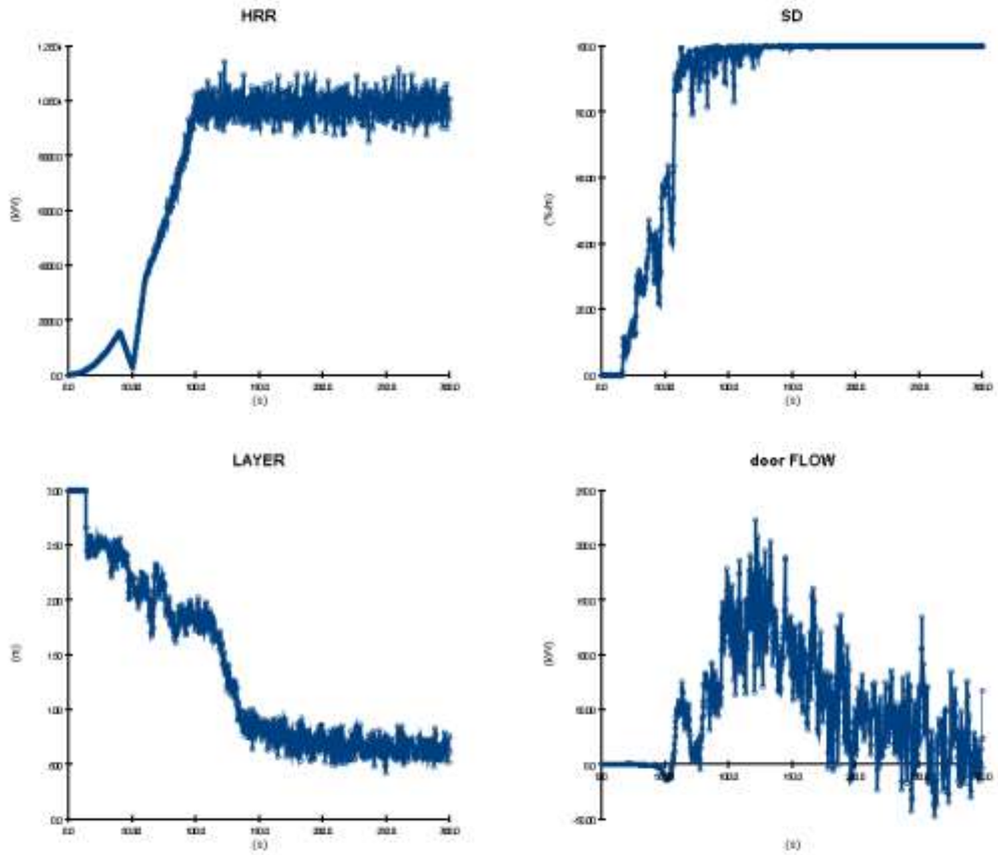


Fig. 7. Summary Key Physical Indicators over the Full 300 seconds Simulation.

In addition, the Smoke Detector (SD) data shows that smoke density began to increase rapidly after 90 seconds. Between 150 and 250 seconds, it spread throughout the corridor, and areas with visibility below 10 meters quickly extended to the exit. Particularly after 180 seconds, visibility near the ceiling above the exit dropped significantly, making it virtually impossible for evacuees to maintain visual awareness.

The LAYER (Smoke Layer Height) graph confirms that after 150 seconds, the height of the smoke layer dropped sharply below 1.0 meters. When the smoke layer falls below 2.0 meters, it reaches the average adult head height, leading to direct exposure of the respiratory system to smoke. If it drops below 1.5 meters, inhalation of harmful concentrations becomes likely, and below 1.0 meter, the environment is considered life-threatening.

DOOR FLOW (Door Flow Rate) refers to the flow rate of substances such as smoke, heat, air, and oxygen through doors, indicating the speed and direction of flow depending on the pressure and temperature differences between indoor and outdoor environments.

The reduction in visibility caused by smoke directly affects evacuation speed. Analysis of the log data shows that when visibility decreased from 10 meters to 5 meters, the average evacuation speed dropped from 1.25 m/s to 0.88 m/s approximately a 30% reduction. In dense smoke conditions where visibility was below 2 meters, some evacuees slowed down further to under 0.5 m/s, leading to collisions with others, disorientation, and decreased mobility. Regarding oxygen concentration, near the ignition source, the O_2 level dropped below 14% after 200 seconds, posing a critical threat to cognitive and motor functions. According to measurements using the FED (Fractional Effective Dose) algorithm, 3.5% of evacuees who remained in areas with oxygen levels below 15% ultimately failed to evacuate.

Conclusion

This study quantitatively assessed how visibility degradation caused by smoke spread influences evacuation behavior during an indoor fire. Over a 300-s simulation the growth of the fire, the resulting smoke propagation, and the corresponding changes in evacuee behavior were analyzed. Smoke severely restricted visibility, lowering mean walking speed by up to 28–30 %. After 150 seconds visibility deteriorated rapidly in key exit and corridor areas, leading to bottlenecks and, in extreme cases, immobility. These findings underscore the importance of rapid evacuation decisions and early route clearance within the first 200 seconds and highlight the need to enhance the response speed of alarm and guidance systems.

Future work should integrate AI-based path-optimization algorithms capable of predicting smoke and visibility in real time and dynamically adjusting evacuation routes. Such systems would benefit from advances in deep-learning object detection, path forecasting, and crowd-density prediction. The present study supplies foundational data for visibility-aware safety design and emergency-response systems and paves the way for simulation-based quantitative-evaluation models and real-time evacuation-guidance technologies that can be deployed in practical settings.

References

[1] Jongjin Lee, Taekeun, “A Study on the Effectiveness of Smart Construction Safety Technology for Vulnerable Groups in Constructio”, The Journal of the Convergence on Culture Technology (JCCT) Vol. 10, No. 1, pp.477-482, January 31, 202

[2] Yuki Akizuki, “Evacuation route design based on visibility for reducing evacuation delays,” Fire Safety Journal, Volume 144, March 2024.

[3] Tokiyoshi Yamada & Yuki Akizuki, “Visibility and Human Behavior in Fire Smoke,” SFPE Handbook of Fire Protection Engineering, pp. 2181-2206, 2016.

[4] B.L. Collins, M.S. Dahir, D. Madrqykowski, “Visibility of Exit Signs in Clear and Smoky Conditions,” Journal of the Illuminating Engineering Society, pp. 69-84, Winter, 1992.

[5] Enrico Ronchi, “Developing and validating evacuation models for fire safety engineering,” Fire Safety Journal, Volume 120, March 2021

[6] ICOMOS. New Zealand Charter for the Conservation of Places of Cultural Heritage Value; ICOMOS NZ (Inc.): Auckland, New Zealand, 2010.

[7] Ministry of Business, Innovation and Employment. CommentaryforBuildingCodeClausesC1-C6andVerification Method C/VM2; Ministry of Business, Innovation and Employment: Wellington, New Zealand, 2013.

[8] Fleischmann, C.M. Is Prescription the Future of Performance-Based Design? Fire Safety Science. In Proceedings of the 10th International Symposium on Fire Safety Science, College Park, MD, USA, 19–24 June 2011.

[9] [C.L. Chow, S.S. Han, G.Y. Han, G.L. Hou, W.K. Chow, “Assessing smoke toxicity of burning combustibles by four expressions for fractional effective dose”, Research Grants Council of the Hong Kong Special Administrative Region, 19 June 2020.

[10] Hartzell GE. Engineering analysis of hazards to life safety in fires: the fire effluent toxicity component. Safe Sci. 2001; 38(2): 147-155.

[11] Chow CL, Han SS, Ni XM. A study on fire behaviour of combustible components of two commonly used photovoltaic panels. Fire Mater. 2017; 41(1): 65-83.