

Natural Human Behaviour in Train Evacuation Simulations: Evidence from a Classroom-Based Experiment

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ABSTRACT

Passenger evacuation during train emergencies is often evaluated using procedural simulation models that prioritise regulatory compliance and idealised passenger movement. Although effective for technical assessment, these models frequently oversimplify human responses and fail to represent realistic passenger behaviour observed in actual emergency situations. As a result, evacuation time predictions may be overly optimistic. This study investigates the influence of incorporating natural passenger behaviours into evacuation simulations compared with conventional procedural approaches. An experimental, classroom-based evacuation simulation was conducted involving thirteen adult participants. Twelve evacuation scenarios were examined, consisting of seven procedural scenarios and five scenarios incorporating natural behaviours. The behavioural scenarios included hesitation, distraction, assisting elderly passengers, carrying luggage, and waiting for companions. Evacuation times were recorded for each trial, participant actions were analysed using video observations, and post-simulation questionnaires were used to capture decision-making and perception. The results indicate that scenarios incorporating natural behaviour produced greater variability and generally longer evacuation times than procedural simulations. The highest behavioural complexity resulted in a maximum evacuation time of 31.4 seconds, with an average increase of 8.58% across behavioural scenarios. Questionnaire findings confirmed that social interaction, situational awareness, and perceived responsibility influenced evacuation behaviour, with social dependency more frequently causing delays than facilitating movement. This study concludes that incorporating realistic passenger behaviour is essential for improving evacuation simulation accuracy and supporting more reliable railway safety evaluation and design.

Keywords: train evacuation, passenger behaviour, emergency simulation, railway safety, evacuation modelling.

INTRODUCTION

Railway transportation is widely recognised as a safe mode of mass transport; however, significant risks remain when emergency situations occur, particularly fires inside trains or tunnels. In such conditions, the success of passenger evacuation becomes a critical factor in minimising casualties and injuries. Consequently, emergency evacuation has long been a central focus in railway safety research [1].

Existing railway evacuation studies are largely dominated by technical approaches that focus on physical and geometrical parameters, such as door width, aisle configuration, passenger capacity, and evacuation time. These approaches have contributed to the development of safety standards and vehicle design regulations, including EN 45545 and NFPA 130. Nevertheless, many of these studies implicitly assume that passengers behave uniformly, rationally, and in full compliance with procedures, which does not fully reflect real emergency conditions [2]. Empirical evidence and post-incident investigations show that human behaviour during emergencies is strongly influenced by psychological and social factors. Passengers may hesitate, delay movement, interact with others, or make spontaneous decisions that deviate from prescribed procedures [3], [4]. Such behaviours can

lead to significant discrepancies between procedural simulation results and real-world evacuation outcomes.

Although evacuation simulation software has advanced significantly, the accuracy of these tools depends heavily on behavioural assumptions and input parameters. At the same time, empirical data on natural passenger behaviour during train evacuations remain limited [5]. Survey-based methods also face limitations due to recall bias and subjective interpretation. This situation highlights a methodological gap between procedural evacuation models and realistic human behaviour.

To address this gap, this study proposes a classroom-based railway evacuation simulation as an alternative methodological approach for studying human behaviour in emergency evacuations. The objective of this research is to evaluate the potential of classroom-based simulations to capture behavioural variability, identify their strengths and limitations, and assess their contribution as a complementary method in railway safety research.

Emergency Evacuation Behaviour Theory

Evacuation behaviour theory commonly distinguishes between the pre-movement phase and the movement phase. The pre-movement phase involves perception, interpretation, and decision-making processes, while the movement phase relates to physical egress towards safety [6]. Empirical studies demonstrate that evacuation delays are frequently dominated by variability in the pre-movement phase, which is strongly influenced by cognitive, psychological, and social factors rather than physical constraints alone [7], [10]. Actions such as waiting for confirmation, collecting personal belongings, or coordinating with group members can significantly extend evacuation time even in environments with sufficient exit capacity [11].

Human behaviour during emergency evacuation is shaped not only by environmental conditions but also by demographic characteristics and social dynamics. Research indicates that age, gender, physical ability, and prior experience influence individual response strategies, walking speed, and interaction patterns during evacuation [7], [9]. Older individuals and passengers with reduced mobility generally exhibit slower movement speeds and may require assistance, while younger adults tend to respond more rapidly but may engage in competitive or risk-taking behaviours [18]. In addition, social relationships, such as family ties or group affiliation, often lead to cooperative behaviours including waiting, helping, or moving as a group, which can alter flow patterns and create localised congestion [8], [11].

Limitations of Conventional Evacuation Modelling

Although evacuation modelling has advanced significantly, many existing approaches prioritise physical parameters such as aisle width, exit size, and walking speed while simplifying or neglecting behavioural variability [12]. Agent-based and flow-based models often represent occupants using average body dimensions and deterministic movement rules, which can produce optimistic evacuation times when pre-movement delays, hesitation, or social interaction are not adequately represented [13], [14]. This limitation is particularly critical in railway contexts, where passenger populations are behaviourally heterogeneous and include individuals carrying luggage, assisting others, or reacting unpredictably under stress [17].

Classroom-Based Evacuation Simulation

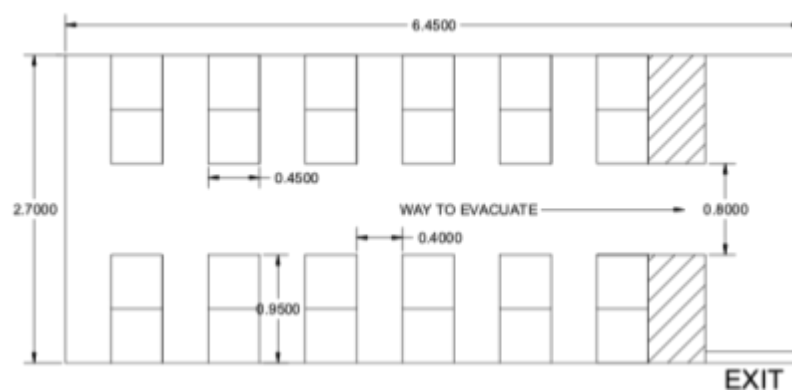
Conducting real-world evacuation experiments under hazardous conditions presents substantial ethical and practical challenges, especially when involving vulnerable participants such as elderly passengers or individuals with disabilities [10]. As a result, controlled experimental settings, including classroom-based evacuation simulations, are widely used to observe behavioural responses in a safe and ethical manner [16]. Classroom-based simulations allow systematic manipulation of behavioural variables, such as delayed response, group coordination, or helping behaviour, which are difficult to isolate in real emergencies [17]. While such simulations cannot fully replicate the emotional intensity of actual disasters, they provide valuable empirical data for understanding human behaviour, calibrating evacuation models, and supporting safety-oriented design decisions [18], [19].

Evacuation research increasingly recognises that realistic safety planning requires integrating physical design considerations with empirical observations of human behaviour [12], [17]. Controlled behavioural studies, including classroom-based simulations, contribute to this integration by capturing micro-level interactions and pre-movement dynamics that are often absent from purely computational models [16]. When combined with simulation tools and existing evacuation theory, these experiments enhance the validity of evacuation assessments and improve the reliability of evacuation time estimates in complex transport environments such as railway systems [19], [20].

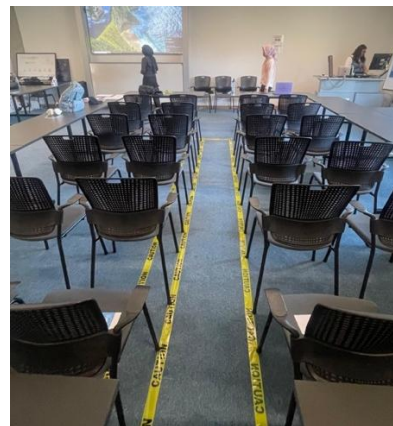
RESEARCH METHODS

Simulation Design

This study employed a classroom-based evacuation simulation using a physical mock-up designed to resemble a train cabin seating layout. Participants were seated according to the layout and received instructions via a pre-recorded video. The evacuation was initiated by a verbal alarm signal, and all participants were directed to evacuate through a designated rear exit.



(a)



(b)

Figure 1. (a) Design of the Layout of Cabin-Like Seating Arrangement
(b) Front and Rear Views

Two categories of scenarios were implemented. Scenarios 1–7 represented conventional procedural evacuations with variations in aisle width, group composition, and luggage obstacles. Scenarios 8–12 incorporated natural human behaviours, such as delayed response, use of mobile phones, moving in the opposite direction, waiting for group members, assisting elderly participants, and obstacles near exits. Approximately 20–30% of participants were assigned predefined behavioural roles to introduce variability while maintaining spontaneous interaction. These roles were not disclosed to other participants. Data collection was conducted using three video cameras placed at the front, rear, and exit areas, supported by stopwatch measurements and post-simulation questionnaires.

Data Collection

Evacuation trials were recorded using three video cameras positioned at the front, rear, and exit of the simulated cabin to capture pre-movement behaviour, movement dynamics, and exit interactions. Video recording was supplemented by manual timing using a stopwatch to measure total evacuation time, defined as the interval between the alarm signal and the exit of the final participant [6].

In addition to video observation, behavioural indicators were documented, including pre-movement activities, route choice, group interaction, obstacle interaction, bottleneck formation, and use of personal belongings. Following the simulation, participants completed a questionnaire designed to capture demographic information, perceived evacuation triggers, decision-making processes, and subjective experiences during the evacuation. Questionnaire-based self-reporting has been widely used to complement observational evacuation data and provide insight into cognitive and social processes.

Data Analysis

A mixed method was adopted to compare procedural and behavioural evacuation scenarios. Quantitative analysis focused on total evacuation time and descriptive statistics, with paired sample statistical tests applied to assess differences between scenario types. Qualitative analysis involved thematic coding of video recordings and observational notes to identify recurring behavioural patterns such as group waiting, hesitation, helping behaviour, and unexpected stops [11].

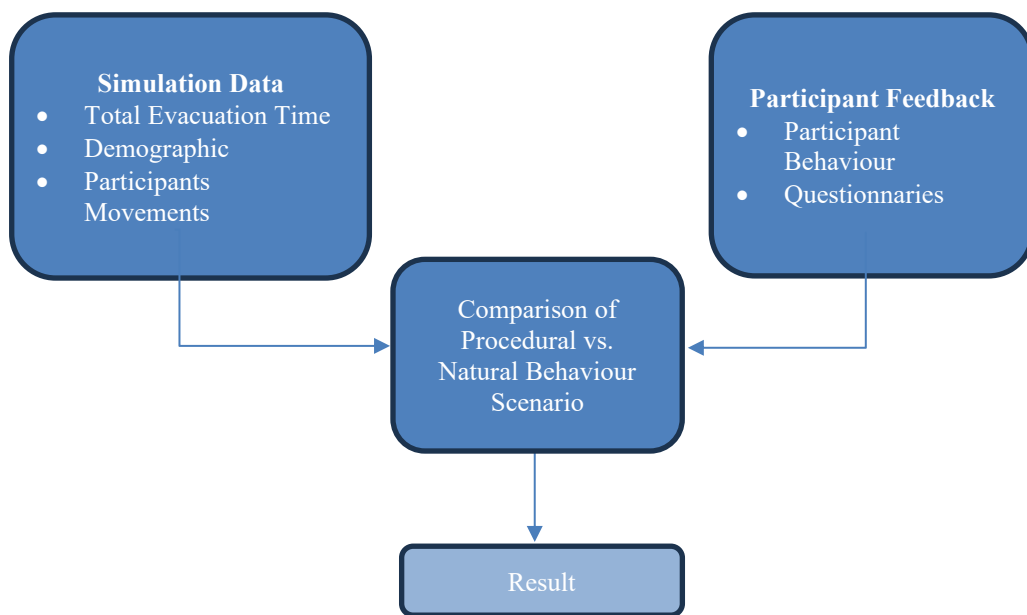


Figure 2. Flow Chart of Comparative Analysis

Finally, quantitative and qualitative findings were triangulated to enhance analytical robustness and reduce methodological bias. Triangulation enabled cross-validation of observed behaviours and evacuation performance outcomes, providing a more comprehensive understanding of how human behaviour influences evacuation processes in controlled environments [16], [19].

RESULT AND DISCUSSION

Evacuation Time Performance

Evacuation times varied across the twelve simulated scenarios, reflecting differences in spatial configuration and behavioural conditions. Procedural scenarios (S1–S7) produced evacuation times ranging from 18.5 s to 29.3 s. The shortest evacuation time was observed in Scenario S7, which featured a wider aisle (80 cm) and no obstacles, indicating the positive influence of increased

available space on passenger flow. In contrast, scenarios with narrower aisles (55 cm), particularly S1 and S2, recorded longer evacuation times within the procedural group.

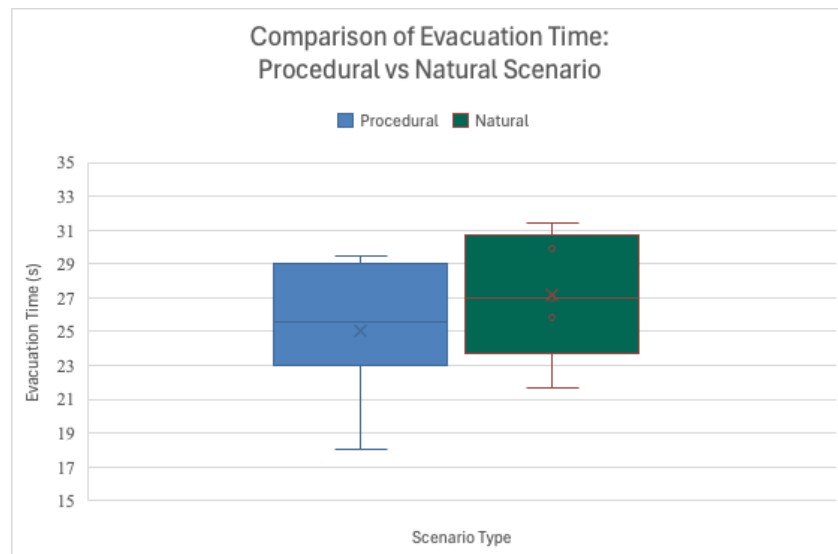


Figure 3. Comparison of Procedural vs Natural Scenario

Scenarios incorporating natural passenger behaviour (S8–S12) exhibited greater variability and generally longer evacuation times. The longest evacuation duration was recorded in Scenario S10 (31.4 s), where multiple behavioural factors occurred simultaneously, including distraction, waiting for family members, assisting a mobility-impaired passenger, and reduced situational awareness. Across all behavioural scenarios, evacuation time increased by an average of 8.58% compared to procedural conditions. These findings indicate that even minor behavioural disruptions can significantly affect evacuation efficiency when combined.

A comparative analysis shows that procedural scenarios demonstrated more consistent evacuation times, whereas natural behaviour scenarios resulted in wider dispersion and higher maximum values, reflecting reduced predictability when realistic behaviour is introduced.

Normality testing using the Shapiro–Wilk method confirmed that evacuation time data for both procedural and natural behaviour scenarios followed a normal distribution, allowing parametric analysis. An independent t-test comparing the two groups indicated no statistically significant difference in mean evacuation times ($p = 0.364$). Although statistical significance was not achieved, natural behaviour scenarios consistently trended toward longer evacuation durations. This outcome is likely influenced by the limited sample size and inherent behavioural variability rather than the absence of behavioural effects.

Observed Evacuation Behaviour

The classroom-based evacuation simulations revealed clear behavioural differences between procedural scenarios and scenarios incorporating natural human behaviour. In procedural scenarios, participants generally responded promptly to the alarm and followed the instructed evacuation route with minimal interaction. Movements were relatively uniform, with limited hesitation and few interruptions during egress. These observations align with idealised evacuation assumptions commonly adopted in simulation-based studies, where occupants are presumed to respond immediately and act independently [6].

In contrast, scenarios incorporating natural human behaviour exhibited greater behavioural variability. Participants frequently engaged in pre-movement activities such as hesitation, observing others, waiting for group members, and assisting individuals perceived as slower or in need of support. Social interactions, including verbal communication and non-verbal coordination, were commonly observed near bottleneck areas such as exits. These behaviours demonstrate that evacuation processes are shaped not only by spatial configuration but also by cognitive and social

factors, supporting previous findings that real evacuation behaviour often deviates from purely procedural assumptions [7], [8].

Survey responses supported the observed behavioural patterns. Most participants (77%) reported following others during evacuation, while only a small proportion acted independently. Approximately 38% indicated hesitation and observation of others before initiating movement, contributing to pre-movement delays. These findings reinforce the role of social cues and collective behaviour in evacuation performance and align closely with the behavioural effects observed in scenarios with longer evacuation times.

Pre-Movement Behaviour and Social Interaction

Pre-movement behaviour emerged as a critical component of the evacuation process. Even within a controlled classroom environment, participants displayed varied decision-making patterns following the alarm signal. Some participants-initiated evacuation immediately, while others delayed movement to assess the situation, collect belongings, or coordinate with peers. These observations are consistent with evacuation behaviour theory, which distinguishes the pre-movement phase as a period dominated by perception, interpretation, and decision-making rather than physical constraints [6].

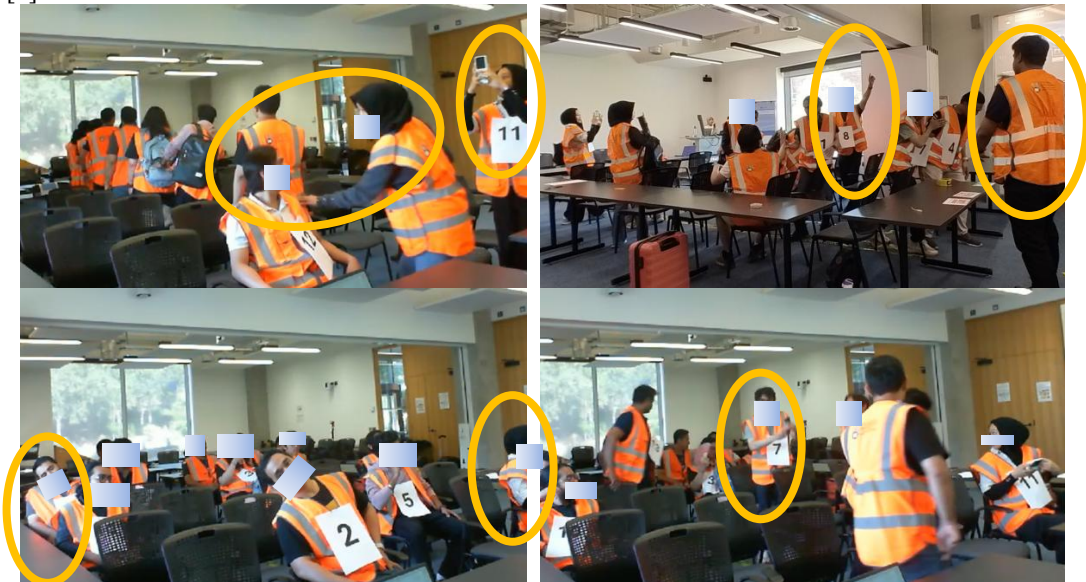


Figure 3. Analysis Combination of Behaviour

Group dynamics further influenced evacuation behaviour. Participants assigned behavioural roles, such as assisting others or waiting at the exit, triggered emergent interactions that affected surrounding participants. Waiting behaviour and informal communication often propagated delays beyond the initially assigned individuals, illustrating how local interactions can influence overall evacuation flow. Similar cooperative and group-oriented behaviours have been documented in real-world evacuation events and experimental studies, where altruism and social attachment frequently outweigh self-serving actions [8], [11].

Implications, Limitations, and Future Research

The results indicate that classroom-based evacuation simulation is effective in capturing qualitative behavioural patterns that are highly relevant to railway emergency contexts. Despite the simplified physical environment, this approach enables controlled observation of key behavioural mechanisms such as hesitation, helping behaviour, and group coordination, which are difficult to isolate in full-scale evacuation drills or real emergencies due to ethical and logistical constraints [10], [17]. The emergence of these behaviours under controlled conditions demonstrates the value of classroom-based simulations as an empirical tool for studying human responses beyond idealised procedural assumptions.

From a methodological perspective, the findings suggest that classroom-based simulations can function as a complementary source of behavioural data for evacuation research. Observed interaction patterns and pre-movement behaviours provide useful insights for validating behavioural assumptions and informing parameter selection in agent-based and activity-based evacuation models. However, the results also confirm that this approach should not be interpreted as a direct predictor of real evacuation times. Instead, classroom-based simulation is more appropriately positioned as an exploratory method for identifying behavioural tendencies and social dynamics that influence evacuation processes [6], [16].

Several limitations must be acknowledged. Participants were aware of their involvement in a study, and hazardous stimuli such as smoke or fire could not be ethically introduced, resulting in lower perceived risk and emotional stress compared to real emergencies. In addition, behavioural roles were scenario-driven rather than empirically calibrated, which limits the direct generalisation of findings. Future research should therefore focus on integrating classroom-based simulations with computational modelling and selected field observations to enhance ecological validity. Such integration would support more realistic representation of pre-movement behaviour and social interaction, ultimately improving the robustness of evacuation modelling and safety analysis [15], [18].

CONCLUSION

This study set out to examine how the inclusion of natural passenger behaviour influences evacuation outcomes in railway emergency simulations and to assess the suitability of a classroom-based simulation method for behavioural analysis. The findings demonstrate that evacuation scenarios incorporating realistic human behaviour consistently resulted in greater variability and longer evacuation durations than procedural scenarios. Increased behavioural complexity, particularly involving social interaction and distraction, produced the longest recorded evacuation time of 31.4 seconds and an average increase of 8.58% across behavioural trials. These results confirm that procedural models alone may underestimate evacuation time when behavioural factors are neglected. Analysis of post-simulation questionnaires supports the simulation results, indicating that evacuation behaviour was strongly shaped by individual decision-making, situational familiarity, and social awareness. Social interaction exhibited mixed effects: while limited coordination occasionally improved movement efficiency, it more frequently caused delays due to waiting for or assisting others. Importantly, behavioural responses emerged primarily through interaction among participants rather than solely from predefined role assignments. The introduction of behavioural variation among a small number of participants was sufficient to trigger spontaneous and adaptive responses from others, highlighting the role of social dynamics in evacuation processes. From a methodological perspective, this research demonstrates that classroom-based evacuation simulations, despite not replicating the full sensory conditions of real emergencies, offer a meaningful and controlled environment for observing behavioural mechanisms. The method enables systematic examination of how behavioural cues, environmental constraints, and interpersonal interactions jointly affect evacuation performance. Overall, the study concludes that evacuation assessments based solely on procedural clearance times risk producing overly optimistic safety evaluations. Integrating behavioural realism into evacuation modelling, training practices, and safety standards can enhance the reliability of railway evacuation analysis and support more inclusive and behaviourally informed safety strategies.

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