

Scaffolded Game-based Simulation Design for Conceptual-Operational Transition in Railway Education

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Abstract: Game-based learning (GBL) has gained increasing attention in engineering education due to its potential to foster learner engagement. However, its pedagogical integration in railway education remains limited. Current digital learning environments in this domain largely rely on high-fidelity systems originally developed for professional operational training. Consequently, they focus primarily on procedural skill acquisition. While these systems provide valuable opportunities for operational training, they offer limited support for developing conceptual understanding before learners engage with complex system interactions. This leaves a gap between theoretical learning and practical application. This study examines the role of game-based approaches in railway and related transport contexts and explores their potential to address this learning gap. To this end, a structured review of existing applications was conducted. Drawing on established frameworks from GBL and gamification research, the analysis identified recurring design patterns and key functional characteristics. The findings indicate that game-based applications in the transport domain remain limited and are primarily used for purposes such as awareness raising or data elicitation rather than conceptual learning. Compared with conventional high-fidelity simulations, more game-oriented applications tend to incorporate staged complexity, bounded decision-making, and explicit feedback. These features are consistent with scaffolding principles but are rarely discussed in terms of helping learners progress from conceptual understanding to operational skills. Based on these findings, this paper proposes Scaffolded Game-Based Simulation (SGBS) as a conceptual framework that introduces an intermediate learning layer between theoretical instruction and high-fidelity simulation. Through progressive complexity and guided interaction, SGBS helps learners move from understanding concepts to applying them in complex domains such as railway education. In this way, simulation-based learning is reframed not only as a tool for skill acquisition but also as a structured pathway that connects conceptual and operational knowledge.

Keywords: Cognitive load, Simulation, Railway education, Transport, Conceptual learning, Scaffolding

1. Introduction

GBL has been widely applied in areas such as language learning (Alexandre et al., 2023) and STEM education (e.g., Freedman et al., 2026; Jokisch et al., 2024; Rosli & Zakaria, 2024), ranging from gamified systems to serious games. More recently, researchers have explored the integration of large language models (LLMs) and smart learning environments to create more adaptive and interactive learning experiences (Goslen et al., 2025; Khosrawi-Rad et al., 2024; Kem, 2022).

In railway education, Simulation-based systems remain the dominant form of digital learning applications. These systems provide valuable opportunities for procedural training and are widely used in practice. While simulation environments may contribute to understanding through practice, key principles and safety rules are often embedded within complex system behaviour and are not directly visible to learners. As a result, novice learners frequently rely on instructor guidance to interpret system responses and understand the consequences of their actions.

GBL offers design features such as progressive difficulty, structured interaction, and explicit feedback (Garris et al., 2002), which can support step-by-step learning and help learners manage complexity. This suggests that GBL may complement simulation-based learning by providing a more guided pathway between theory and practice.

This paper therefore proposes SGBS as an intermediate learning layer between theoretical instruction and high-fidelity simulation. The framework aims to deepen learners' understanding of key concepts before they engage with complex simulation environments, enabling them to approach practical tasks with greater confidence while also supporting reflection on those concepts during practice. To investigate this approach, the following research questions are addressed:

- How are game-based applications currently used in the railway and broader transport domain?
- How can GBL be designed to support the transition from theoretical instruction to simulation-based practice in railway education?

While engaging with recent literature in this field, the analysis repeatedly pointed back to a set of well-established foundational theories, which therefore serve as the theoretical foundation of this study.

2. Background

2.1 Learning Challenges in Complex Simulation Environments

Simulation-based learning environments in domains such as railway systems integrate multiple layers of complexity, including system behaviour, operational rules, and interface interaction. For novice learners in particular, managing these aspects simultaneously can impose substantial cognitive demands.

According to cognitive load theory (Sweller, 1988), such conditions may exceed learners' cognitive capacity. Attention must be divided between understanding system logic, operating interfaces, and completing tasks. As a result, learners may focus on performing actions rather than grasping the underlying principles. Although repeated practice can improve operational proficiency, it does not necessarily foster conceptual understanding. Furthermore, when task demands exceed learners' capabilities, maintaining engagement becomes difficult. This may negatively affect motivation (Cziksentmihalyi, 1990).

These challenges highlight the need for structured learning support. Scaffolding (Wood et al., 1976; Vygotsky, 1978) addresses this need by enabling learners to tackle complex tasks through guided, incremental steps. By limiting interaction complexity and making key principles more accessible, scaffolding helps learners build understanding before engaging with more complex simulation-based tasks. This raises the question of how such support can be incorporated into learning environments.

2.2 GBL as Scaffolded Environments

In this context, GBL has been proposed as an approach to support interactive and experiential learning. Beyond its motivational aspects, GBL can be understood as a design approach that structures learning through progressive challenges, guided interaction, and continuous feedback (Garris et al., 2002; Naseer et al., 2025). These characteristics align with the principles of scaffolding, as they enable learners to engage with complex systems in a stepwise and manageable manner (Goslen et al., 2025). Through structured interaction and explicit feedback, game-based environments can make underlying principles more visible to learners and support the gradual development of competence (Garris et al., 2002; Gee, 2004). As such, GBL may provide a useful intermediate layer between theoretical instruction and complex simulation-based practice (Szilas, 2025).

However, this potential is not inherent, but depends critically on how gameplay elements are designed. A central challenge lies in aligning engaging gameplay with intended learning outcomes, ensuring that interaction supports rather than distracts from learning (Urgoa et al., 2022). This highlights the need for a more systematic approach to designing game-based learning environments.

3. Context: Railway Simulation and Education

Railway systems are complex socio-technical systems characterised by tightly coupled interactions between infrastructure, rolling stock, operational processes, and human decision-making (Wilson et al., 2007; Rodrigue, 2013). Due to their track-guided nature and the "iron-on-iron" interaction between wheel and rail, train movements are strictly constrained and require coordinated control through signalling and interlocking systems to ensure safe and conflict-free operations (Pachl, 2025).

To manage this complexity, a wide range of simulation applications has been developed in the railway domain. These applications can be broadly distinguished according to their primary purpose. Some are designed for system analysis and optimisation, such as timetable and capacity simulations (e.g., FBS, OpenTrack, and SUMO), while others are intended for training and education, including driving simulators and interlocking simulators. Originally developed for professional training, these simulators are widely used to prepare operational staff such as train drivers and dispatchers. Their primary purpose is to help users apply theoretical knowledge and develop operational skills in realistic scenarios. Although they are increasingly adopted in higher education (Lautala et al., 2011), they largely retain the design logic of professional training environments. Consequently, learners may become proficient in carrying out operational tasks without fully

understanding the underlying system logic and safety principles. For novice learners in particular, the complexity of these environments often necessitates continuous instructor support, making independent exploration difficult. This may limit sustained engagement (Cziksentmihalyi, 1990; de Jong, 2010).

Some of the simulation-based systems discussed above are occasionally described as serious games, suggesting a degree of overlap between simulation and GBL (Schwan, 2006). However, these concepts are not equivalent. Simulation-based systems do not automatically constitute GBL environments. As highlighted by Martens et al. (2008), GBL can be understood as the integration of learning, simulation, and game elements (see Figure 1). In many existing railway applications, game-related elements remain limited, and learning processes are rarely designed with explicit pedagogical objectives in mind.

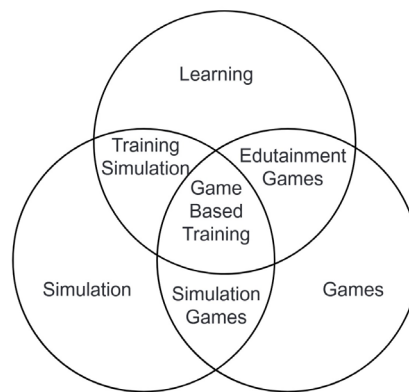


Figure 1: Interplay of pedagogy, computer science and games (Martens et al., 2008)

In summary, railway education is typically characterised by a progression from theoretical instruction to simulation-based training. While simulation environments provide valuable opportunities for operational practice, they largely retain the design logic of professional training systems. As a result, the pedagogical role of GBL in railway education remains insufficiently defined. This highlights the need for design approaches that intentionally align gameplay, learning objectives, and system representation.

4. Analysis of Existing Applications

An exploratory literature review was conducted to identify game-based and simulation-based applications in railway, transport, and related domains. The review serves as the empirical basis for the conceptual framework proposed in this study. The search was based on combinations of keywords related to game-based learning, gamification, serious games, and digital learning applications, together with domain-specific terms such as railway, transport, mobility, and interlocking. Given the limited number of studies in railway education, the search scope was extended to related transport and industrial contexts where comparable learning challenges could be observed. The initial search was intentionally broad and aimed to identify existing applications and examine the purposes they were designed to serve. Following relevance screening, 20 studies were selected for detailed coding and analysis. The analysis was primarily informed by the Input–Process–Outcome model of Garris et al. (2002), which provided a structure for examining game characteristics, learning processes, and educational outcomes across the identified applications. The resulting observations were subsequently synthesised into broader design dimensions that informed the development of the proposed framework.

4.1 Results of the Literature Analysis

Table 1 summarises the analysed studies and their key characteristics, providing the basis for the subsequent analysis. Based on these observations, the study derives design-relevant insights for simulation-based learning in railway education, with a particular focus on how learners can be supported before engaging with complex operational tasks.

Table 1: Overview of selected studies and their key characteristics

	Modes of Use			User Group				App Type				Knowledge Dimension				Design Dimension			
Scientific Publication	Persuasion	Elicitation	Assimilation	Drivers	Commuters / Passengers	Formal Learners	Industry Professionals	Institutional Actors	Training Simulation	Game-Based Learning	Gaming Simulation	Gamification	Conceptual	Procedural	Skill-Based	Not Mentioned	Feedback Transparency	Principle Representation	System Realism
Alderliesten et al. 2019	x			x					x			x					/	/	/
Chan et al. 2016			x		x			x					x				○	○	↑
Feinauer et al. 2022			x	x							x	x					●	●	↓
Hu et al. 2024			x		x			x					x	x			○	○	↑
König et al. 2017	x			x					x			x					/	/	/
Kurapati et al. 2017	x	x					x			x		x					/	/	/
Lafkihi et al. 2019		x					x			x		x					/	/	/
Lamotte et al. 2019			x	x				x							x		○	○	↑
Martí et al. 2025	x	x		x							x				x		/	/	/
Meijer et al. 2012		x				x	x			x		x					/	/	/
Meng et al. 2021		x	x		x			x					x	x			○	○	↑
Rajaonah et al. 2018			x		x	x			x			x	x	x		-	○	→	
Rossetti et al. 2013		x					x		x						x		/	/	/
Sharma et al. 2017			x	x		x		x							x		○	○	↑
van den Hoogen & Meijer 2015		x					x			x		x					/	/	/
Vanichchanunt et al. 2023			x	x	x	x		x				(x)	x	x			○	○	→
Wang & Abbas 2018			x		x				x			x					●	●	↓
Wang et al. 2021			x		x			x				(x)	x				○	○	↑
Wohlstein et al. 2023			x		x				x			x					●	●	↓
Yue et al. 2022			x		x			x					x	x		-	○		↑
Legend: ○ = implicit; ● = explicit; - = not mentioned; ↑ = high; → = medium; ↓ = low;																			
(x)= stated as a goal, but without explicit implementation or design support																			

4.2 Modes of Use -Game-based Applications in Transport Domain

Based on their primary function, game-based applications in railway and transport contexts can be grouped into three modes of use: persuasion, elicitation, and assimilation (Rossetti et al., 2013). These categories are reflected in Table 1. As assimilation-oriented applications are of particular relevance to the proposed framework, their associated design dimensions are indicated separately.

The analysis indicates that persuasion-oriented applications are most commonly implemented as gamified systems or serious games with simplified scenarios, typically targeting general users such as commuters or passengers. Their primary aim is to raise awareness or influence attitudes or behaviour rather than support deeper learning processes. For example, Martí et al. (2025) integrated a gamification module into a demand-responsive transportation application to encourage users to accept modifications to their travel requests, thereby reducing operational costs related to travelled distance and vehicle maintenance. Similarly, Alderliesten et al. (2018) developed the game *MainTrain*, which teaches commuters about rail maintenance

while simulating the relationship between maintenance activities and passenger satisfaction, fostering empathy and a better understanding of the need for scheduled maintenance.

Applications designed for elicitation are frequently used to gather domain-specific data, for example in research contexts or decision-support systems. Their primary users are often institutional actors, and they are commonly implemented as simulation-based environments that allow users to manipulate system parameters and observe system responses. For example, the Dutch railway system has applied gaming and simulation approaches to support innovation processes (van den Hoogen & Meijer, 2015). They report a gaming simulation session in which traffic and train controllers were required to manage a disruption on the corridor between Amsterdam and Eindhoven. The session was used to explore the feasibility of different train control concepts under conditions of high-frequency passenger operations.

Assimilation-oriented applications are primarily intended to support learning and skill development in educational and training contexts. Within railway education, they are predominantly implemented as high-fidelity simulations or simulators that closely replicate real-world operational environments. This is exemplified by Hu et al. (2024), who designed and developed an integrated virtual reality training simulation system that supports multiple railway operation scenarios, including dispatching, driving, and inspection tasks. A similar approach can be observed in Yue et al. (2022), who developed a virtual simulation experiment platform for high-speed railway traction power supply systems. The system integrates engineering data and simulates key equipment and operational scenarios, enabling learners to engage in tasks such as equipment inspection, electrical design, and engineering case analysis within a highly realistic environment. When broadening the scope beyond railway-specific applications to the wider transportation domain, a different type of approach can be observed. In contrast to these high-fidelity simulation environments, this approach focuses more explicitly on supporting conceptual understanding through simplified game structures. For example, Wang and Abbas (2018) develop web-based educational games targeting key concepts in transportation engineering, including traffic planning, signal control, and highway design. Compared with high-fidelity railway simulators, these applications place greater emphasis on conceptual learning through simplified interaction and progressive complexity.

4.3 Design Characteristics of Learning-oriented Applications

Building on this categorization, the analysis examines how different types of applications are designed and what characteristics they exhibit in relation to learning processes. The focus is placed on assimilation-oriented applications, as these are most relevant for educational and training contexts.

High-fidelity simulations aim to replicate real-world operational environments and primarily support procedural training. Although conceptual understanding is often stated as a learning objective, it is not always explicitly represented in system design. As a result, learners may become proficient in executing tasks without fully understanding the underlying mechanisms that govern system behaviour. At the same time, the high complexity and associated cognitive load of these environments can obscure system dynamics and causal relationships, further limiting the development of conceptual understanding. A further limitation of these systems concerns the nature of feedback, which is frequently implicit or delayed. As a result, learners are required to infer the consequences of their actions from system responses, for example through performance disruptions or delayed outcomes. This feedback structure may limit opportunities for iterative exploration and experimentation, which are often considered important for learning environments that aim to support “safe-to-fail” experiences. In practice, the time and effort required to recover from unsuccessful actions in such systems may reduce the willingness of learners to explore alternative strategies.

In contrast to high-fidelity simulations, some learning-oriented applications employ simplified game or simulation environments that place greater emphasis on conceptual understanding. Three recurring design characteristics can be observed: staged complexity, structured decision-making, and explicit feedback. First, simplified environments often reduce system complexity and allow learners to explore underlying principles without being overwhelmed by operational details. For example, Wohlstein et al. (2023) developed an animated simulation platform that enables learners to manipulate parameters and observe resulting system dynamics. Second, learning activities are frequently structured through constrained decision spaces and progressive challenges. MainTrain (Alderliesten et al., 2018), for instance, introduces increasing levels of difficulty while illustrating the consequences of infrastructure maintenance decisions. Third, explicit feedback mechanisms are commonly used to make action–outcome relationships more transparent. In MainTrain, passenger satisfaction directly reflects the consequences of player decisions, while the web-based educational

games developed by Wang et al. (2018) provide visual feedback through colours and points. Such mechanisms support guided exploration and make underlying system principles more visible to learners.

Taken together, the comparison reveals four recurring design dimensions that distinguish learning-oriented game-based applications from conventional high-fidelity simulations: (1) system complexity, (2) decision-making structure, (3) feedback, and (4) the explicitness of system principles.

High-fidelity simulations prioritise realism and procedural skill development, but often embed key principles implicitly within complex system behaviour. In contrast, simplified game-based approaches reduce complexity, constrain decision spaces, and provide explicit feedback, making causal relationships and underlying principles more visible to learners. Rather than requiring learners to infer system principles indirectly through operational performance, these environments support understanding through guided exploration and interaction. These differences highlight their complementary roles and suggest the potential of using simplified environments as an intermediate, scaffolded layer between abstract conceptual instruction and high-fidelity simulation.

The analysis suggests that the key distinction between existing simulation approaches is not primarily whether they address conceptual or procedural knowledge, but rather how explicitly underlying principles are made accessible to the learner. This highlights a gap between system-level simulation and principle-level understanding, particularly in the transition from conceptual knowledge to operational performance.

5. Scaffolded Game-based Simulation: A Conceptual Framework

From a cognitive perspective, learning can be understood as a progression across both knowledge dimensions (e.g., conceptual to procedural) and cognitive processes (e.g., understanding to application), as described in Anderson and Krathwohl's (2001) revision of Bloom's taxonomy. Transitions across knowledge and cognitive dimensions do not occur automatically but require scaffolded instructional support. However, in railway education, these transitions are not always explicitly addressed in the design of existing learning approaches. The findings presented in Section 4 indicate that learning-oriented game-based applications frequently incorporate scaffolding characteristics such as reduced complexity, structured decision-making, and explicit feedback. These features enable learners to engage with system principles before entering realistic operational environments. Together, these characteristics suggest that GBL can facilitate the transition from conceptual understanding to procedural application. Building on this observation, we propose SGBS as an intermediate stage between theoretical instruction and high-fidelity operational training.

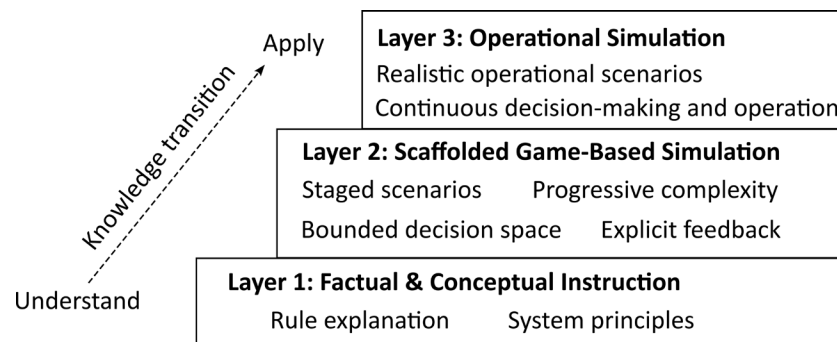


Figure 2: Conceptual Framework for Scaffolded Game-Based Simulation (SGBS)

Figure 2 presents the proposed SGBS framework, which structures simulation-based learning as a progressive transition from conceptual understanding to operational performance. To illustrate the proposed framework, the teaching of flank protection is used as an example. Figure 3 illustrates an example learning flow implementing the proposed framework. In Layer 1, learners are introduced to the underlying safety principles and the rationale behind flank protection. In Layer 2, learners engage with simplified game-based scenarios of increasing complexity. Initial activities focus on identifying conflicting routes and selecting appropriate flank protection measures, while later tasks introduce guided route-setting activities that familiarise learners with simulator operations. Immediate feedback supports both conceptual understanding and procedural development by explaining incorrect decisions and guiding learners toward appropriate solutions. In Layer 3, learners apply these principles within a high-fidelity interlocking simulator. This progression supports the transition from understanding signalling principles to applying them in realistic operational and signalling design contexts.

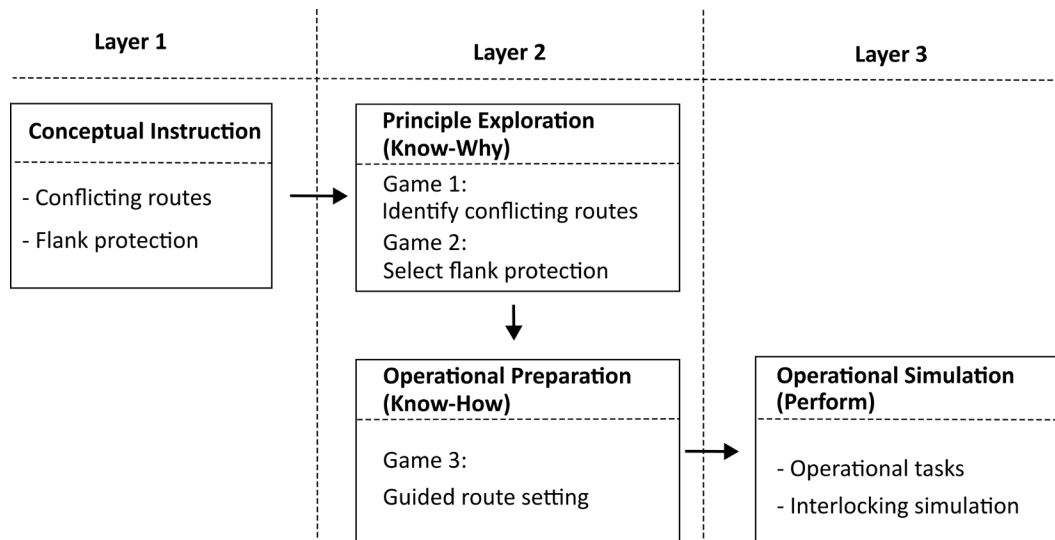


Figure 3: Example Implementation of the Proposed SGBS Framework

6. Discussion

GBL in the railway domain remains at an early stage of development. Current simulation-based approaches in the railway sector are predominantly oriented toward practice and skill acquisition. While these environments provide valuable operational experience, they offer limited support for structured conceptual understanding without appropriate instructional design (Makransky & Petersen, 2021). The findings of this study suggest that integrating GBL as an intermediate layer can help bridge this gap by providing more guided and accessible learning experiences, supporting the transition from conceptual knowledge to practical application.

This study contributes a conceptual design perspective for simulation-based learning environments by introducing a scaffolded layer. This layer may be integrated into existing simulation systems or implemented as a separate GBL application that prepares learners for high-fidelity simulation, supporting a gradual transition from conceptual understanding to operational competence (Kirschner et al., 2006).

Although developed for railway education, the proposed approach may also be applicable to other domains characterised by complex systems and demanding operational training. Its implementation requires aligning domain-specific knowledge structures with appropriate learning objectives and game mechanics (Arnab et al., 2015).

A limitation of this study lies in the conceptual nature of the proposed framework. The SGBS approach has not yet been empirically validated. Future work should focus on implementing and evaluating the framework in practice.

Ethics Declaration: This research did not require ethical approval as it does not involve human or animal subjects.

AI Declaration: AI-based tools (ChatGPT, OpenAI) were used during the preparation of this paper to support language refinement, improve clarity of expression, and assist in structuring academic arguments. The AI was also used to suggest alternative phrasings and to provide feedback on drafts.

All content, including the research design, conceptual framework, analysis, and interpretations, was developed by the authors. The authors critically reviewed and edited all AI-generated suggestions and take full responsibility for the final content of the paper.

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