

Interactive Signalling Laboratory: A Physical Serious Game for Railway Operations Education

Martin Scheidt¹ and Julek Weck²

¹Hochschule Darmstadt, Germany

²TU Braunschweig, Germany

martin.scheidt@h-da.de

j.weck@tu-braunschweig.de

Abstract: Railway operations are a complex socio-technical system shaped by state-based logic, relational dependencies, and temporal constraints that are difficult to visualise. Many core principles remain implicit and are only indirectly accessible through regulations, diagrams, or operational rules, which makes railway operations difficult to teach. Conventional teaching approaches often reach their limits when conveying such dynamic, interdependent systems. Although digital railway simulations are widely used, they primarily support individual interaction through abstract interfaces. There is still a need for collaborative, haptic learning environments that encourage shared reasoning and make implicit operational knowledge visible. Therefore, this paper introduces the Interactive Signalling Laboratory (SigLab), a physical serious game based on a modified wooden railway. It teaches railway operations through the interplay of vehicles, signalling, and infrastructure. SigLab applies a discrete abstraction of a continuous system, with speed represented as track segments per round. This serves a didactic purpose by making principles discussable that would be harder to observe in a continuous simulation. Its core didactic principle is collaborative gameplay, requiring learners to operate the system jointly and negotiate terminology, thereby rendering otherwise invisible rules tangible. Because state updates are performed stepwise on local track segments in fixed rounds, SigLab can be interpreted as behaving like a cellular automaton. Physical interaction is assumed to support the externalisation and negotiation of tacit mental models. However, systematic documentation of physical game-based approaches in this domain remains limited. To address this gap, SigLab is presented as a practice-based case study refined over seven years. Practice-based insights suggest that SigLab supports shared concept formation, improves system-level understanding, intensifies peer-to-peer dialogue, and fosters systematic reasoning about operational processes. Learners must articulate assumptions and resolve conflicts collaboratively. Open challenges remain regarding model granularity, scalability, and assessment integration. The paper contributes design insights for physical serious games in higher education. It identifies the need for systematic evaluation and outlines next steps toward empirical validation, aiming to inform future work on game-based learning for complex, rule-driven systems.

Keywords: Physical serious games, Collaborative learning, Railway operations, Engineering education, Tangible learning environments, Cellular automaton

1. Introduction

Teaching railway system technology poses specific didactic challenges. Subsystems such as interlocking exhibit a high degree of hidden complexity: essential operational rules and dependencies remain implicit, and the processes that govern train movement are not directly visible.

The tight coupling of infrastructure, operations, signalling, and vehicle dynamics easily leads to cognitive overload. Learners often compensate for this by relying on inadequate mental models derived from familiar systems, such as road traffic.

These factors highlight the need for instructional approaches that make system logic explicit, reduce abstraction through appropriate representations, and support the gradual development of accurate mental models.

Numerous railway games and simulation tools exist, especially digital ones. While these systems can model complex operations, their underlying rules often remain embedded in software and are not directly visible to learners. Digital approaches also tend to emphasise individual interaction, limiting collaborative reflection and shared reasoning.

This reveals a gap in approaches that combine physical and haptic representations with collaborative interaction. Tangible systems can provide shared representations of abstract concepts and support discussion, yet many such approaches are insufficiently documented for reproduction and systematic study across contexts.

2. Related Work and Research gap

Against this background, serious games are an established approach for supporting learning and engagement across domains (Wilkinson, 2016). They are particularly useful for teaching complex, rule-based systems, where traditional methods often struggle to convey dynamic interactions and dependencies (Michael and Chen, 2005). Railway operations are a typical example of such systems, combining safety-critical rules with temporal and

spatial constraints. A review by Connolly *et al.* (2012) reports generally positive effects of serious games on learning and engagement, while noting that most evidence concerns digital games.

Within game-based learning, digital and physical modalities can be understood as a spectrum rather than a strict dichotomy. Digital games offer advantages in scalability, automation, and the representation of complex systems. In contrast, physical and tangible games can make abstract concepts more accessible (Marshall, 2007), while embodiment and multimodal interaction are important in learning processes (Price and Jewitt, 2013).

SigLab builds on these considerations through a deliberately physical, tangible approach. A wooden railway provides a familiar and playful medium. At the same time, the system introduces a discrete abstraction of railway operations, representing speed as fields per round. The setup requires players to coordinate actions and discuss system behaviour. These design choices align with the tangible interaction framework described by Hornecker and Buur (2006) and with collaborative learning mechanisms based on shared manipulation, as discussed by Rick *et al.* (2009).

Physical railway games for education can be grouped into two strands. The first is exemplified by well-specified shunting puzzles such as Inglenook Sidings and Timesaver, documented by Wymann (2001), where conditions, constraints, goals, and procedures are described in enough detail for replication and comparison. The second comprises practice-oriented formats that foreground socio-technical coordination and communication (Meijer and Perpinya, 2012; Birte Thomas, 2017; Kühne-Henrichs, 2019; Suter and Inglese, 2021), but these accounts are often more anecdotal and provide less explicit specification of mechanics and rule systems. As a result, the first strand more readily generates transferable knowledge, whereas the second often remains context-bound and difficult to evaluate across implementations. In both strands, abstraction from real railway operations is unavoidable; the key distinction is how explicitly the resulting model is defined. For both strands, including SigLab, empirical validation remains an open research task.

To address this gap, this paper presents the **Interactive Signalling Laboratory (SigLab)** as a practice-based case study developed and refined over seven years, documenting design decisions, deployment contexts, and lessons learned from the use of a physical, game-based learning environment for railway operations.

3. SigLab Artefact and Materials

SigLab consists of wooden toy rails and trains, 3D-printed infrastructure elements, and a printed **handbook**. The choice of material was deliberate: most learners are already familiar with these components from childhood, creating a low-barrier and playful point of entry. The handbook structures tutorials, scenarios, and debrief prompts and serves as a shared procedural reference during play. Figure 1 provides an annotated overview of an assembled display scenario.

Standard straight or curved **track** pieces and mechanically settable turnouts form the modular basis for building several scenarios with different layouts. In game-mechanical terms, each track segment counts as one field, and the joints between segments define the track joints. A set of standard wooden vehicles represents a **train**. SigLab provides three consist types: local service (two vehicles), long distance (four), and freight (seven). Speed is represented as track segments per round. Each train is operated with a **control board** comprising a tally counter (round and travelled fields), a hand-operated train lever, and a train-specific laminated dynamics card for acceleration and braking; lever positions range from 0 (standstill) to 5 segments per round.

Some 3D-printed elements can be placed at track joints to regulate train movements. Both track joints and 3D-printed elements are equipped with magnets to hold components in place. Several elements can also be arranged at one track joint.

Distant and block signals consist of a lever that changes the visible aspect; the stop aspect (red) can be pinned to represent route-related locking. The **route signal** externalises interlocking checks, with one pin position per condition. The **direction manager** has three lever positions (left, neutral, right) and can be pinned to represent granted direction. Block and route **clearing points** are labels placed on track joints. **Overlap markers** sit on track segments and may be overrun by vehicles. A **switch lock** fits onto the turnout knob and can be pinned to indicate that points must not be changed while a route is set.

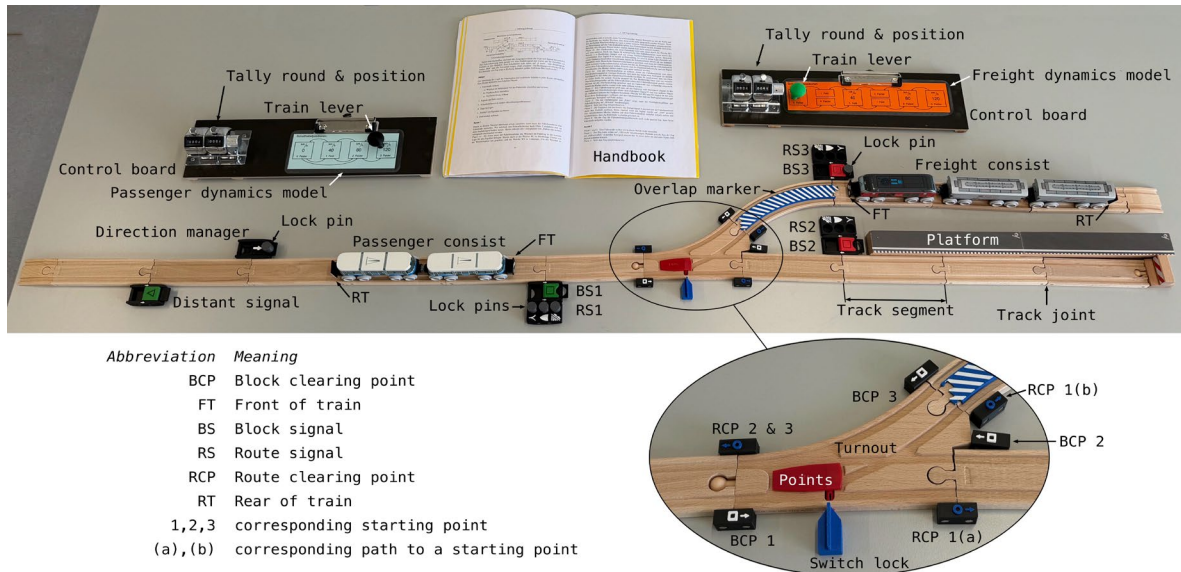


Figure 1: Full scene of the game components

The estimated cost of one complete SigLab set is approximately EUR 1008 (see Table 1). Producing the custom components requires a 3D printer, a drill press, adhesive, and optionally a laser cutter; no additional specialist equipment is needed.

A complete game set can be stored in a portable case and weighs approximately 11.2 kg including the case. A typical scenario layout spans roughly 6.5 m of track. With strategic use of curves, it fits on two to three standard classroom tables and can be assembled in five to ten minutes.

Durability improved substantially across iterations. Several components in version 1 were made out of wood and proved fragile or impractical; these issues were addressed in version 2, which is the version described in this paper. At present, ten sets are in use: five version-1 sets at TU Braunschweig, upgraded with version-2 turnouts; four version-2 sets at Stadler Signalling; and one version-2 set at Hochschule Darmstadt, donated by Stadler Signalling.

Table 1: Bill of materials for one SigLab kit. Prices are approximate (2025).

Item	Description / Supplier	Qty	Unit price	Estimated cost
Track infrastructure				≈ 369 €
Straight track	2/3 length, 144 mm, milled both sides (Eichhorn)	60	≈ 1.75 €	≈ 105 €
Curved track	1/1 curve, 170 mm (Eichhorn)	12	≈ 2.00 €	≈ 24 €
Ramp & buffer stop	Ramp with buffer (BRIO / Eichhorn)	2	≈ 15 €	≈ 30 €
Turnouts (L + R)	Settable switch, 144 mm (BRIO)	2 + 2	≈ 15 €	≈ 60 €
Platform	tiny stationz Berlin + Hamburg (tiny trainz)	6	≈ 25 €	≈ 150 €
Magnets & adhesive				≈ 36 €
Neodymium disc	5 × 3 mm (track joints)	472	≈ 0.05 €	≈ 24 €
Neodymium disc	8 × 8 mm (train lever)	2	≈ 1.00 €	≈ 2 €
Adhesive	Transparent, metal on wood & PLA, 125 g	1	≈ 10 €	≈ 10 €
Control boards				≈ 113 €
Tally counter	Two-bank, chrome, base mount (tallycounter.co.uk)	2	≈ 35 €	≈ 70 €
Board & battens	Wooden base for control board	2	≈ 10 €	≈ 20 €
Metal foil	Magnetic surface for board	2	≈ 5 €	≈ 10 €
Clipboard clips & graphics	Clips + laminated coloured paper	2 + 3	-	≈ 13 €

Item	Description / Supplier	Qty	Unit price	Estimated cost
Rolling stock				≈ 170 €
Local-service consist	Two-part train (LaLok.at)	1	≈ 40 €	≈ 40 €
Long-distance consist	Four-part train (LaLok.at)	1	≈ 60 €	≈ 60 €
Freight consist	Locomotive + 5 wagons (LaLok.at)	1	≈ 70 €	≈ 70 €
3D-printed components				≈ 145 €
Signals, markers, jigs, etc.	See SigLab-3Dmodels repository (≈ 820 g PLA total)	≈ 70	-	-
PLA filament	Black, white, green, red, yellow, blue	6	≈ 20 €	≈ 120 €
Support filament	PVA or PLA/PETG support	1	≈ 25 €	≈ 25 €
Packaging & storage				≈ 175 €
Systainer Combi M337	Anthracite, with office lid + foam (Tanos)	1 set	-	≈ 95 €
Insert boxes	50 × 50 mm and 50 × 100 mm compartments (Tanos)	6 + 6	≈ 5 €	≈ 60 €
Printed handbook (binder)	Printed manual in binder	1	≈ 20 €	≈ 20 €
			Total	≈ 1008 €

4. Modelling Approach and Game Mechanics

At the conceptual level, SigLab is designed around three interdependent commitments: a tangible medium that keeps system states visible, collaborative operation that forces assumptions and rule interpretations into shared discussion, and the deliberate absence of automatic rule enforcement, so that safety logic must be enacted by the players themselves (Hornecker and Buur, 2006; Price and Jewitt, 2013).

SigLab does not model a specific national signalling system. Instead, it adopts the generic, nation-independent perspective proposed by Pachi (2024) and focuses on those principles that are shared across railway operations. The aim of SigLab is to help learners understand the underlying logic that different signalling systems implement in different forms. Two concepts are central to this abstraction: the route as the basic unit for safe train movements, and blocking-time theory as a way of describing how infrastructure is reserved, occupied, cleared, and released over time.

To make these principles playable, SigLab translates a continuous system into a discrete game model. Space is divided into movement units called fields. Time is divided into rounds, so that every state change becomes observable as a separate step. Speed is represented as track segments per round. This discretisation serves a didactic purpose, because it makes relationships between distance, speed, braking, route occupation, and release visible and discussable in a way that would be harder to observe in a continuous simulation.

Within this discrete model, the blocking-time becomes observable to the players. Because train movement, signal setting, route locking, and release are enacted round by round, the reservation and release of infrastructure become visible as a stepped temporal pattern. A particularly important example is the timely clearance of the distant signal: only if it is set early enough can the train continue without stopping at the next main signal.

Some elements therefore differ deliberately from their real-world counterparts. First, SigLab distinguishes between **distant signals** (green or yellow aspect), **block signals** (green or red aspect), and **route signals** (checkbox for interlocking conditions). In many real signalling systems, the functional difference between block protection and route protection is combined in one main signal. SigLab separates these functions so that learners can see more clearly whether a movement authority depends on block availability or on a route that has been made safe through a turnout area. Second, SigLab **clearing points** indicate a direction of travel. This differs from typical railway practice, but it makes the release logic visually traceable on the layout, especially on bidirectional lines, because players can immediately identify to which movement direction a clearing point belongs.

The model also leaves out important aspects of real railway operations. Some simplifications follow directly from the physical medium of the wooden toy train, especially the absence of detailed vehicle physics and technical infrastructure processes. More relevant are the less visible omissions: SigLab does not model communication

between signaller and driver, automatic train protection, degraded modes of operation, or human factors such as reaction time and fatigue. These boundaries did not arise entirely in advance, but emerged through iterative design. Over time, the game was focused on those relationships most useful for introductory learning: train dynamics, signal dependencies, route locking, and section release. More advanced operational layers can be addressed on the basis of this simplified but analytically explicit representation.

Each round follows six phases in a fixed order:

1. **Set routes:** Players set, lock, and make the required route safe.
2. **Clear signals:** Signals are only cleared once the route has been made safe.
3. **Adjust train lever:** Players change the train lever according to the train's dynamics model.
4. **Move trains:** Trains move by the number of fields allowed by the current lever position.
5. **Set signals to stop:** Signals passed by a train are returned to stop.
6. **Release routes:** Routes are released after the train has passed the relevant clearing point.

The fixed order is analytically important. It reproduces the fundamental principle that infrastructure must be made safe before movement is authorised, while also making the temporal relation between preparation, movement, and release visible to the players.

5. Roles, Facilitation, and Scenario Design

Train movement is constrained by train-specific dynamics cards that relate lever position to speed in fields per round. Since the lever changes by at most one step per round, trains cannot accelerate or brake discontinuously. Figure 2 illustrates a simple movement sequence.

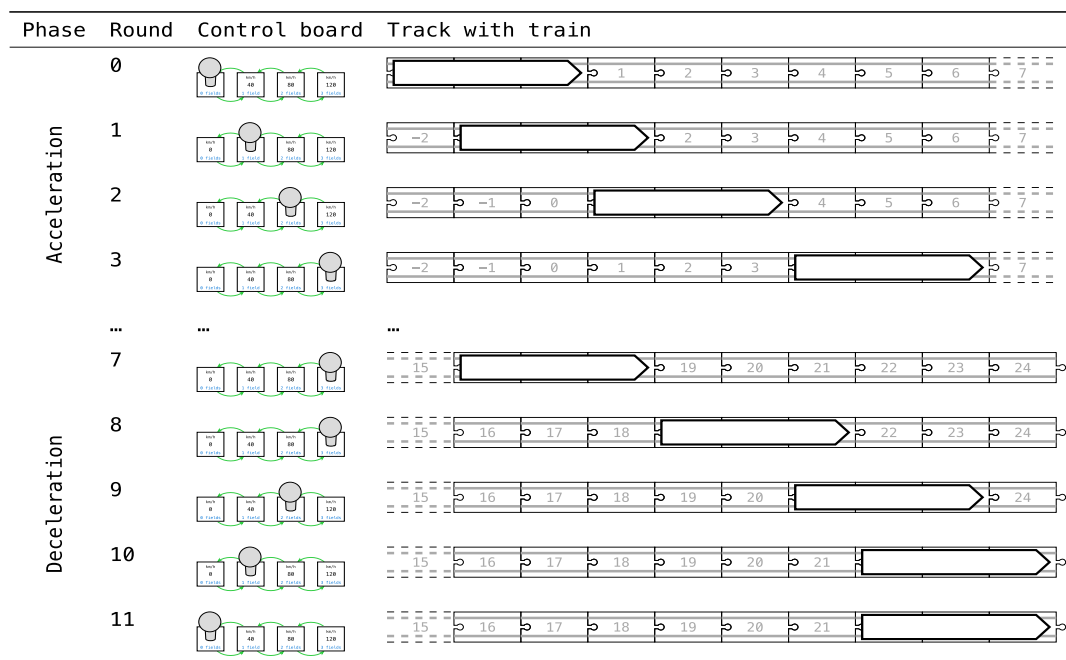


Figure 2: Stepwise movement example for acceleration and deceleration

Acceleration and braking are observable in reality, but the driver experiences them only locally rather than from a bird's-eye perspective. In SigLab, this bird's-eye view renders braking distance as a countable number of fields, from which the necessary placement of the distant signal can be derived directly. Figure 2 also reveals characteristic effects of discrete modelling. In round 11, the lever is reduced from one field per round to zero before movement is executed, so the train remains stationary; this follows directly from the round structure, in which lever adjustment (phase 3) precedes movement (phase 4). By contrast, round 7, in which the lever remains at maximum despite the upcoming stop, may be interpreted as representing the driver's reaction time before braking begins.

SigLab assigns distinct roles to its players. Typical small scenarios involve one facilitator, one signaller, and one or two drivers, while more advanced or network-scale scenarios distribute work across several signallers, drivers, and sometimes dispatchers.

The facilitator has a central role. In tutorials, this person guides the group through the scenario, keeps the round and phase sequence intact, and checks whether the intended state has been reached before the group proceeds. This role is pedagogically important because SigLab externalises interlocking logic into player actions. Participants can only play meaningfully if they already know, at least in simplified form, which conditions must be checked before a signal may be cleared or a route released.

Each game set includes a printed handbook which serves both as the facilitator's guide and as a shared reference for the group during play. It structures play as a progression from tightly guided tutorials to increasingly open-ended scenario tasks. The tightly guided tutorials specify the roles, material, initial setup, round structure, and expected end state in detail; they therefore function as worked examples that let participants rehearse the procedural logic of the game before they are asked to solve problems independently. Later tasks retain the same underlying mechanics but shift the emphasis from rule following to analysis and design. After each completed task, the handbook calls for a short discussion with the instructor before the next scenario begins, which supports self-directed work without removing the need for facilitation.

Scenarios progress from a single train with stepwise acceleration and braking, to block protection with multiple trains, to route protection in turnout areas, and finally to network-planning and traffic-management problems that require players to combine braking distance, signal dependency, route locking, and release into integrated operational decisions. Typical tasks include determining travel times and stopping positions, and calculating minimum block spacing. Participants have to place distant and main signals within braking and sighting constraints, or determine the departure order of trains with different dynamics. They must also allocate routes where turnout speed limits, overlaps, and conflicting movements interact. In the largest scenarios, participants design a small network and operate several train services through it, turning the game from a local signalling exercise into a simplified operations-planning problem.

6. Deployment and Iterative Refinement

The primary institutional setting is the transportation engineering curriculum at TU Braunschweig, where SigLab has been used since 2019 across 14 semesters with approximately 350 students. The game is not a stand-alone activity but a structured teaching format embedded in courses on railway operations and signalling, best used alongside an accompanying lecture that introduces the relevant principles before the hands-on session. Learners work in small groups around separate game sets while the instructor moves between groups, answers questions, and uses plenary phases to relate the simplified game model back to real railway practice. Rather than replacing lectures, SigLab complements them by letting learners test abstract concepts against a shared physical model and negotiate operational decisions collaboratively. SigLab's present form resulted from iterative refinement between 2019 and 2025. Early paper prototypes tested the core game mechanics and assessed pedagogical viability before investing in more elaborate material production. A first consolidated version, developed within project funding and originally called "BRIOgame", translated the didactic concept, handbook, and materials into a wooden format. This step rested on the assumption that the medium's material qualities substantially shape the play experience. Figure 3 summarises this development trajectory.

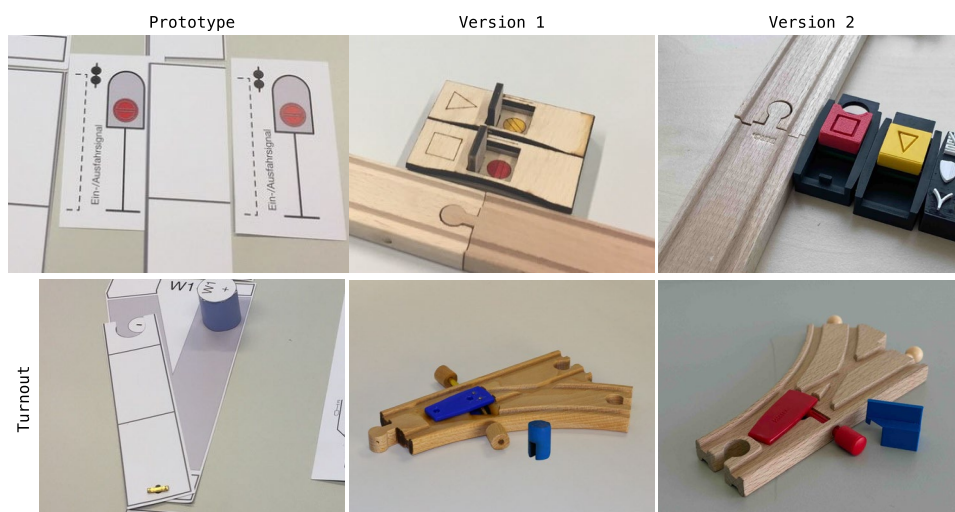


Figure 3: Iterative refinement for different versions

This assumption was revised in a later version: feedback from practical use informed the redesign of track joints and locking mechanisms. To simplify production, the design shifted towards greater use of 3D-printed components, which had previously been employed only selectively. In parallel, the handbook and scenario sequence continued to be refined to simplify the rules and clarify the sequence of play. The figure contrasts early paper-based signals and turnout aids with later wooden and 3D-printed components; this process remains ongoing.

Following these refinements, the format has also proved transferable beyond this university context. Additional sets are used in professional training at an industry partner and at another higher-education institution, following the same implementation pattern: short conceptual input, guided entry into the rules, collaborative scenario work, and instructor-led reflection. SigLab has also been employed as a visualisation tool in EU-funded research projects.

7. Practice-based Observations

The observations in this section are practice-based. They draw on teaching and debrief experience across the settings described above, photographs, iterative revisions of the handbook and scenarios, recurring participant comments during play, and occasional transfer sessions at TU Wien, KTH Stockholm, and other demonstrations. The claims should therefore be read as informed practice observations rather than measured learning outcomes.

A recurring pattern is that many participants initially try to solve early scenarios mentally and treat the layout as optional. This changes once variables increase and errors accumulate across rounds. At that point, the game functions as intended: less as a toy and more as a stepwise simulator whose rules generate train movements and infrastructure states.

This transition is especially clear in tasks involving braking distance, block clearance, and the relation between main and distant signals. The slowed-down, discrete progression helps learners discuss operational dependencies that are often hidden in real traffic: why braking distance constrains signal placement, how faster and slower trains require different separations, and when a block can be considered clear for a following movement. The abstraction into fields and rounds also proved useful for discussing generic relations, such as overlaps of one to three fields, without becoming tied to exact real-world dimensions.

The format also exposes misconceptions that are difficult to correct through prior explanation alone. Because the full layout is visible, participants often assume that all actors share the same information. During play, groups can discuss why drivers, signallers, and infrastructure do not operate with identical knowledge, and how information depends on place and time. Across sessions, the strongest perceived “aha” effect was a spatial sense of operational consequences, especially how train sequencing choices propagate through the system.

More concretely, repeated use showed that SigLab was strongest where it made otherwise hidden relations spatially visible. The clearest example was the link between long braking distances, distant signalling, and the spacing needed for conflict-free train operation. The shared physical layout also supported peer explanation: when one participant made an error, others could usually point to the exact location and state where the misunderstanding had arisen. Informal reactions further suggested that the wooden railway format attracted curiosity and lowered the entry barrier, although this effect was not systematically documented. In one recurring university format, some students voluntarily completed the final multi-kit scenario outside scheduled class time.

Several practical limits also recurred. Discrete modelling can introduce unintuitive discretisation effects when continuous processes such as braking are represented in rounds. Some participants struggled with converting real distances into fields, or with tracking which train had already moved in a round. Overlaps proved particularly difficult to model and explain, which led to repeated redesign. Participation also dropped noticeably when more than three players shared one kit. Larger network or dispatching scenarios were hard to run at all, because they required many sets, many participants, and substantial facilitator attention.

8. Discussion and Limitations

Finally, the format was time-sensitive and facilitation-intensive. Sessions shorter than about 90 minutes usually allowed only the first scenario, leaving little time for mistakes, comparison, and reflection. Even with longer sessions, widely spaced meetings made re-entry harder. Facilitation remained decisive: instructors had to prompt learners to use the artefact, diagnose errors as complexity increased, and translate game situations back into railway practice. The most efficient analytical solutions were typically introduced by facilitators after exploratory play. Formal assessment was limited, since pre-/post-testing is not built into the course formats.

The shared physical layout slowed the proceedings down and gave participants a common point of reference for demonstrating, explaining, and verifying states, which proved particularly important for collective reasoning and peer explanation. These effects did not arise from physicality alone, but also from deliberate simplification. The format was best suited to concepts that need to be grounded in physical constraints — braking distance, block spacing, and the relationship between movement authority and sighting distance — whereas topics driven by formal rule logic, such as detailed interlocking behaviour, would likely be better supported by digital tools.

The case also suggests clear boundary conditions: SigLab worked best with small groups, manageable scenario size, explicit abstraction, sufficient time for debriefing, and active facilitator support. Under these conditions, the most defensible claim is not that physical games are generally superior to digital simulation, but that a shared, slowed-down physical model can make otherwise abstract operational relations discussable in a particularly vivid way.

At the same time, this paper does not claim a measured effect of SigLab on learning outcomes. The evidence presented here is anecdotal, retrospective, and practice-based. It is therefore affected by facilitator bias, selective recall, context dependence, and the absence of a comparison group. A more systematic evaluation is in preparation, but those results are not yet available.

There are also limits in the model itself. SigLab deliberately abstracts away from national operating rules and many details of real railway practice in order to foreground generic system effects. This makes it a conceptual teaching tool rather than a substitute for professional training. Because the model remains discrete in its treatment of time, distance, and speed, neither the rule-based behaviour of railway staff nor the continuous character of real operations can be transferred directly from the game.

Finally, reuse is constrained by implementation effort. Although the materials are openly available, a working set still has to be sourced in parts, modified, printed, and assembled. The current wooden format also brings practical burdens: weight, storage, transport, maintenance, room requirements, setup time, and facilitator expertise. Some of these constraints are inherent to the present material form; others may be reduced through further development, for example through lighter construction methods or electronic support for interlocking logic.

9. Conclusion and Next Steps

This paper contributes three elements: a documented case of a physical teaching artefact, a modelling approach that translates generic railway system relations into a discrete tabletop format, and a teaching design refined through repeated use in higher education and professional training. The case suggests that SigLab's main value lies not in realism as such, but in its ability to turn a familiar toy-like object into a shared simulation that supports discussion of braking, signalling, and block logic.

These claims remain provisional. The case indicates that SigLab can repeatedly surface insights that support learners' mental models, but it does not yet establish the magnitude or durability of learning effects. The next step is a more systematic evidence base through pre- and post-session evaluation and closer study of how facilitation shapes learning.

The next practical step is to improve replicability. Core materials — including the handbook, 3D-print files, and a paper prototype — are openly available through the project resources (RailEduKit, 2026). Broader reuse would benefit from clearer assembly instructions and a simplified material setup.

Acknowledgement

This work was supported by the Innovationsprogramm Gute Lehre "teach4TU" of Technische Universität Braunschweig, which enabled practical classroom deployment, and by Stadler Signalling Deutschland GmbH, which supported iterative development.

AI Declaration: This manuscript is classified as [TLP:AI](#) AI:GREEN (AI-assisted): AI tools were used only for language editing, manuscript structure, not for data analysis or result generation. All substantive content and interpretation were reviewed and approved by the authors, who take full responsibility.

Ethics Declaration: Ethical clearance was not required for this practice-based educational case study.

Author Contributions: Conceptualisation of SigLab: M.S.; methodology and modelling framework: M.S., J.W. and contributors; game design refinement and adaptation: M.S., J.W. and contributors; case-study documentation

and original draft preparation: M.S.; review and editing of the manuscript: M.S., J.W. Both authors read and approved the final manuscript.

References

- Birte Thomas, R.M., Jan Grippenkov (2017) "Bahnbetrieb im Serious Game," *Der Eisenbahn Ingenieur*, pp. 31–33.
- Connolly, T.M. et al. (2012) "A systematic literature review of empirical evidence on computer games and serious games," *Computers & education*, 59(2), pp. 661–686. <https://doi.org/10.1016/j.compedu.2012.03.004>.
- Hornecker, E. and Buur, J. (2006) "Getting a grip on tangible interaction: A framework on physical space and social interaction," *Proceedings of the SIGCHI conference on human factors in computing systems*. New York, NY, USA: Association for Computing Machinery (CHI '06), pp. 437–446. <https://doi.org/10.1145/1124772.1124838>.
- Kühne-Henrichs, A. (2019) "Auf dem Weg zur Systemkompetenz," *Der Eisenbahn Ingenieur*, pp. 18–20.
- Marshall, P. (2007) "Do tangible interfaces enhance learning?" *Proceedings of the 1st international conference on tangible and embedded interaction*. New York, NY, USA: Association for Computing Machinery (TEI '07), pp. 163–170. <https://doi.org/10.1145/1226969.1227004>.
- Meijer, S. and Perpinya, X. (2012) "Gaming simulations for railways: Lessons learned from modeling six games for the dutch infrastructure management," *Infrastructure design, signaling and security in railway*, pp. 275–294.
- Michael, D.R. and Chen, S.L. (2005) *Serious games: Games that educate, train, and inform*. Muska & Lipman/Premier-Trade.
- Pachl, J. (2024) *Railway signalling principles: Edition 3.0*. Edition 3.0. Braunschweig. <https://doi.org/10.24355/dbbs.084-202405240811-0>.
- Price, S. and Jewitt, C. (2013) "A multimodal approach to examining 'embodiment' in tangible learning environments," *Proceedings of the 7th international conference on tangible, embedded and embodied interaction*. New York, NY, USA: Association for Computing Machinery (TEI '13), pp. 43–50. <https://doi.org/10.1145/2460625.2460632>.
- RailEduKit (2026) "Interactive signalling laboratory (SigLab): Project resources." <https://web.archive.org/web/20260610124833/siglab.railedukit.org/> (Accessed: June 10, 2026).
- Rick, J. et al. (2009) "Learning by doing with shareable interfaces," *Children, Youth and Environments*, 19(1), pp. 320–341. <http://www.jstor.org/stable/10.7721/chilyoutenvi.19.1.0320> (Accessed: March 29, 2026).
- Suter, J. and Inglese, T. (2021) "Neue Methode für den Aufbau und die Erhaltung von Sprachkompetenzen von Lokführern und Fahrdienstleitern," *Eisenbahntechnische Rundschau (ETR)*, (1+2), pp. 17–21.
- Wilkinson, P. (2016) "A brief history of serious games," *Entertainment computing and serious games*. Springer International Publishing, pp. 17–41. https://doi.org/10.1007/978-3-319-46152-6_2.
- Wymann, A. (2001) "Model railways shunting puzzles website." <https://web.archive.org/web/20010501000000/wymann.info/ShuntingPuzzles/> (Accessed: March 30, 2026).