# Teleoperation in Rail and Tram Systems: A Scoping Review on Work Design, Roles, Tasks, and Human–Machine Interfaces

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**Abstract:** As rail transport becomes increasingly automated, ensuring effective human fallback solutions is critical to safety and performance. Teleoperation enables remote intervention, but research on human roles, workplaces, and performance is fragmented. This scoping review maps *current concepts and technologies* for teleoperation in rail and tram systems, emphasizing the central roles of human operators and human–machine interface design. This results in an in-depth synthesis of teleoperation studies and identification of key task clusters.
Following PRISMA guidelines, a systematic literature search was conducted in five databases. Of 505 unique publications, 71 met the inclusion criteria after title and abstract screening. After full-text analysis, 59 studies were included and categorized into teleoperation (n = 21) and control room contexts (n = 38). Results reveal a wide variety of publications from various perspectives on teleoperation in the rail domain. Included studies ranged from prototype workplaces and interface concepts to task and activity analyses. However, validated performance metrics, comparative studies, and consistent theoretical grounding remain scarce. The findings highlight the need to better integrate human factors, ergonomics, and system design in future research on railway teleoperation.

**Keywords:** Human Factors, Railway remote control, Human-Machine Interface, Teleoperation, PRISMA
**Disclaimer:** ChatGPT and Grammarly were used to check and optimize the outline and grammar in the submitted publication.

## 1. Introduction

The increasing automation of rail and tram systems raises fundamental questions regarding the integration of human fallback solutions when automated agents reach the limits of their operational design domain (Stene, 2018; Üyümez et al., 2024). While teleoperation has been widely discussed as a promising strategy in road-based and cross-domain mobility contexts (e.g., Wahlström et al., 2015), research in the rail domain remains fragmented and technology-driven. Existing work addresses either remote driving concepts (e.g., Gadmer et al., 2021), operator support in control rooms (Brandenburger & Naumann, 2018), or isolated prototype workplaces (Michel et al., 2025). In the railway domain, teleoperation or remote control is predominantly discussed as an event-based intervention strategy, in which human operators are involved in ambiguous, degraded, or safety-critical situations that exceed the capabilities of automated systems (Brandenburger et al., 2018; Üyümez & Oetting, 2020). This use case is beyond passive monitoring and highlights the need to

understand the demands of human–machine interaction, cognitive requirements, and design constraints for future teleoperation workplaces (Cort & Lindblom, 2025). At the same time, only a few empirical studies investigate operators' information needs, interface design, and the evaluation of teleoperation systems with respect to usability, workload, and performance metrics. To address these gaps, this literature review examines the conceptual, technological, and ergonomic landscape of teleoperation for rail and tram systems. It synthesizes current research to identify design implications, methodological shortcomings, and open challenges. The following research questions guide the process of the review:

**RQ1:** Which tasks and roles are described for remote operators in rail and tram teleoperation?

**RQ2:** Which workplace and workstation designs (including prototypes) are currently used for remote interaction and control?

**RQ3:** Which human-machine interface (HMI) design guidelines, principles, or interface concepts are proposed for teleoperation in rail-based systems?

**RQ4:** How are teleoperation workplaces and prototypes evaluated, particularly with respect to human factors, usability, workload, and performance metrics?

Due to the limited space, only the results for RQ1 are described in detail. The other results are available in OSF and will be published elsewhere. By systematically synthesizing these aspects, the review provides a structured foundation for further requirements analysis for these types of workplaces. It supports the development of human-centered teleoperation concepts for future rail mobility.

## 2. Method

A systematic literature search was conducted in five databases (IEEE Xplore, ACM Digital Library, Scopus, Web of Science, and TRID) following PRISMA guidelines (Page et al., 2021). Search strategies were adapted to the metadata structure of each database, using title-, abstract-, and keyword-based queries where available. The search query consists of the following terms connected with Boolean operators:

(rail* OR railway OR railroad OR tram* OR "light rail" OR metro OR subway OR train) AND
(teleoperat* OR "remote operat*" OR "remote assist*" OR teledriv* OR "remote control" OR "control room" OR "remote operation center" OR ROC) AND
(workstation OR workplace OR console OR ergonom* OR HMI OR "user interface" OR human)

The query was slightly adapted to align with the database requirements for wildcards and available search definitions. All results were downloaded and imported into Zotero to remove the duplicates. The screening phase was twofold. First, titles, keywords, and abstracts were screened in SysRev[1]. The inclusion and exclusion criteria are predefined and manually screened for by the first author. Inclusion criteria were defined as containing 1) explicit reference to rail- or tram-based transportation (e.g., railway, metro, light rail, tram-train), 2) relevance to teleoperation, including remote control, remote assistance, or remote supervision, and 3) consideration of human factors, HMI, workplace aspects, or the role of a human remote operator. Publications were excluded when they did not meet these criteria or addressed purely technical automation topics without human involvement. During abstract screening, SysRev decision rules with Boolean labels ensure consistent classification. The labels "domain:

[1] Project available: https://www.sysrev.com/u/97708/p/262852

rail/train transportation," "phenomenon: teleoperation," and "considering workplace/ HMI/human" needed to be true to include a publication for the full-text analysis. This resulted in 71 publications being identified as relevant. Afterwards, the availability and context are checked with the full texts. The publications are subdivided into two groups for the context of control rooms (n = 38) and distinct teleoperation (n = 21). One publication was excluded from the full-text analysis because it primarily addresses e-learning processes rather than teleoperation. This review analyzes 20 publications on railway teleoperation. The PRSIMA search flow is illustrated in Figure 1.

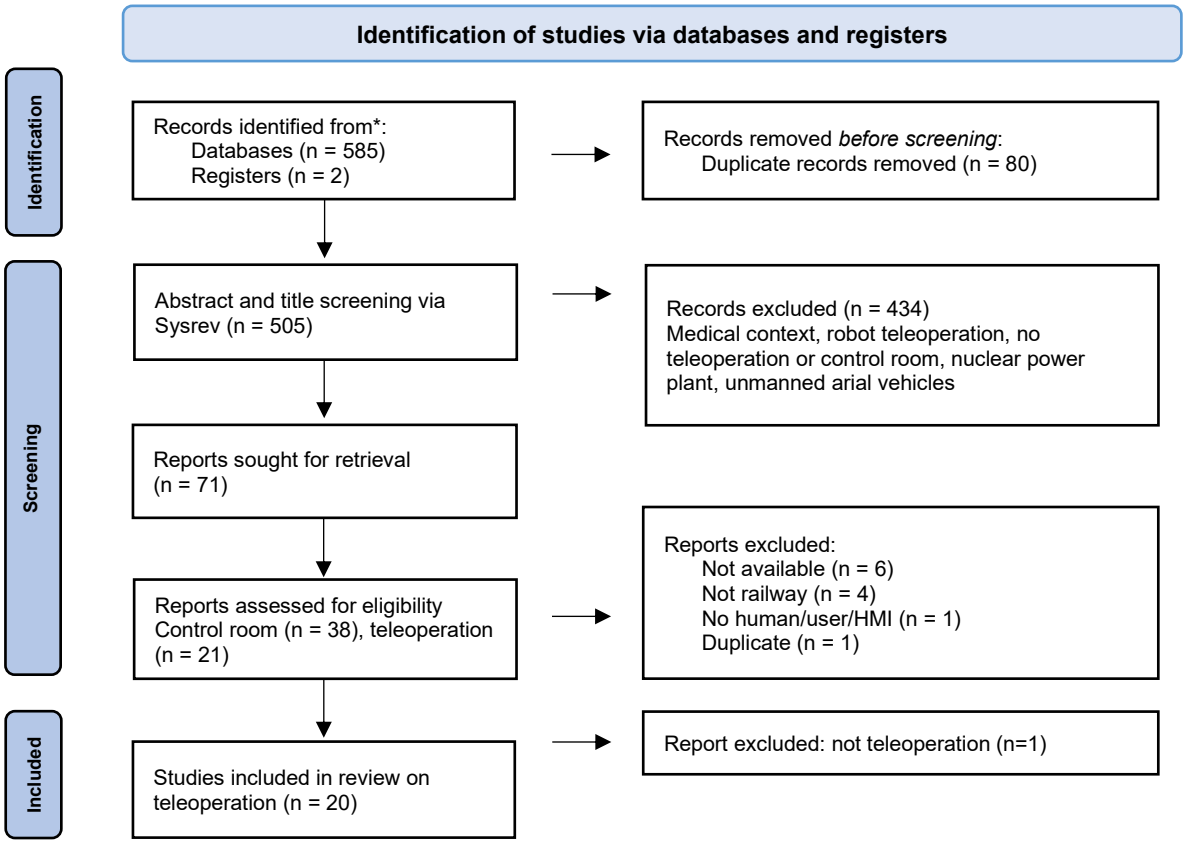


***Figure 1**: Summary of the search process, abstract and full text screening* (Page et al., 2021)

In the second phase, the 20 full-texts are analyzed and subdivided into analysis (n = 5), study (n = 8), and other categories, including conceptual publications, reviews, and framework articles (n = 7). All additional information regarding the searches, screening phases, and results is provided in OSF[2].

## 3. Results

The 20 reviewed publications span from 2007 to 2025, with a clear concentration (75%) published after 2018, indicating a growing research interest in recent years and sustained relevance of the topic up to the present. The literature predominantly focuses on the rail domain (n = 14, part of the criteria), with few studies addressing mixed transport systems (n = 5) and contributions to metro systems (n = 1). The majority of the publications (n = 9) focus on *remote driving* and (n = 8) *supervision*. *Remote*

[2] Additional data: https://osf.io/gb7me/overview?view_only=d36ee8a1653248958cf12f395c610ce5

*assistance* in terms of decision-making support without remote driving is not addressed in the identified publications, indicating a strong research emphasis on direct control and oversight roles rather than on supportive teleoperation concepts. Based on these publications and their references, teleoperation refers to the ability of a human to sense and manipulate a system through a set of techniques that transpose action capabilities from a remote location (Garrec et al., 2010; Michel et al., 2025). This remote operation is done without direct sensory contact to the teleoperated system (Wahlström et al., 2015). Applied to remote train control (RTC), this describes the act of driving railway rolling stock and engaging with other agents at a distant site to ensure safety, even in environmentally challenging situations or when the technical system malfunctions (Gadmer et al., 2022; Morin et al., 2024). This definition already highlights the different roles and related tasks for remote operators.

Across the reviewed literature, a broad range of tasks and roles associated with teleoperation in the railway domain are reported. Rather than describing a single, homogeneous teleoperator role, this review inductively categorizes tasks into five task clusters that vary in their temporal structure, operational scope, and level of responsibility (Table 1).

***Table 1:*** *Summary of task clusters identified based on the selected publications.*

| Task cluster | Examples of specific tasks | References |
|---|---|---|
| Remote driving (direct control) | Traction and braking control; speed and power management; compliance with speed limits; manual route following via symbolic track maps; low-speed maneuvering; driving on sight during fallback | Gadmer et al., 2021, 2022; McDonald et al., 2014; Michel et al., 2025; Pacaux-Lemoine et al., 2020; Young Kim et al., 2019 |
| Monitoring & supervision | Continuous monitoring of automated train movements; supervision of system states; vigilance during prolonged low-activity phases; detection of irregular situations | Brandenburger et al., 2021; Brandenburger & Naumann, 2018; Cummings et al., 2025; Dobson, 2015; Wahlström et al., 2015 |
| Intervention & recovery | Handling automation-triggered intervention requests; diagnosing abnormal situations; short-term manual control during degraded modes; recovery and retrieval of automated trains | Brandenburger & Naumann, 2018; Reinach et al., 2007; Stene, 2018; Üyümez et al., 2024; Üyümez & Oetting, 2020 |
| Understanding & sensemaking | Interpreting abstract system representations; constructing situation awareness at a distance; anticipating conflicts, disruptions, and delay cascades; anomaly identification | Cort & Lindblom, 2025; Gadmer et al., 2021, 2022; Karvonen et al., 2011 |
| Coordination & organizational | Coordination with dispatch, maintenance, and emergency services; alignment of actions across roles and systems; system-level decision-making during disruptions | Dobson, 2015; Křižan et al., 2024; Morin et al., 2024; Wahlström et al., 2015 |

The first cluster comprises *remote driving* tasks, which involve continuous or event-based manual control of a train. This direct control includes traction and braking, speed management, and compliance with operational constraints. These tasks are described in studies on remote locomotive driving (e.g., Young Kim et al., 2019) and fallback operation (e.g., Brandenburger et al., 2021), in which teleoperation replaces onboard driving for extended periods or during recovery scenarios. A second cluster relates to *monitoring and supervision* tasks. Operators continuously observe automated train movements and system states, often across multiple vehicles. Studies adopting this perspective emphasize vigilance, sustained attention, and the ability to detect and diagnose irregular situations (Berdal et al., 2025). Closely related are *intervention and recovery* tasks. They occur when the rail automation reaches its operational limits or

when an intervention request is triggered. These tasks include diagnosing abnormal conditions, assuming control for short periods, and restoring safe system operation in degraded modes. Unlike continuous remote driving, intervention tasks are episodic and mostly safety-critical (Cummings et al., 2025). Some studies highlight *understanding and sensemaking* tasks, focusing on the cognitive work required to construct situational awareness despite spatial distance and reduced sensory cues. This is further extended to an accurate understanding of the capabilities and risks of the railway automation system. Example tasks include interpreting abstract representations, translating them into actionable decisions, anticipating disruptions, and predicting system limitations (Karvonen et al., 2011). *Coordination and organizational* tasks occur mainly in publications that aim for a system framework or adopt a managerial perspective (Morin et al., 2024). These tasks involve coordination across organizational units, communication with external agents (technical, other remote agents, authorities), and participation in shared decision-making processes during exceptional situations.

Overall, comparison across studies reveals a fundamental distinction between continuous task structures (e.g., remote driving) and event-based task structures (e.g., supervision and intervention). The perspective of the publications strongly influences which task clusters are emphasized and which role is highlighted. The individual clusters should not be viewed as independent of one another. On the contrary, most teleoperation workplaces combine various tasks from other domains (Wahlström et al., 2015). In summary, the reviewed literature describes remote operators in rail and tram teleoperation as hybrid operational roles whose tasks range from continuous remote driving and system monitoring to event-based intervention, recovery, diagnosis, and coordination, with the specific role configuration depending on the operational context, level of automation, and analytical perspective of the respective studies.

## 4. Conclusion

This review provides a structured overview of research on different tasks and human roles in railway teleoperation. It includes the diversity of concepts, approaches, and implementations of teleoperation. The reviewed literature should be understood as a starting point for deeper, empirically grounded investigations. Future research should focus on comparative studies, laboratory human factors studies to advance understanding of task-related information processing in teleoperation, and tests of solutions to theoretically derived problems to contribute to human-centered rail-based teleoperation.

## 5. Literature

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