

Towards safe remote operation of automated buses: A systematic review of insights from comparable domains

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For automated buses to become viable, remote operators must supervise multiple vehicles from dedicated control rooms. Experiences from comparable domains such as maritime, aviation, and industrial automation show that remote monitoring and assistance introduce safety-critical challenges related to human performance, system transparency, and human-automation collaboration. This paper presents a scoping review using PRISMA methodology across Scopus, IEEE Xplore, and TRID, synthesizing studies on remote operation of automated buses and relevant insights from comparable domains. The studies are mapped onto a holistic work-system model to identify challenges involving the operator, tasks, technology, organization, and work environment. Drawing on socio-technical system theory and research in Human-Computer Interaction (HCI) and Computer-Supported Cooperative Work (CSCW), we recommend that future research includes user centered design studies conducted in realistic work environments, and that the further development of remote operations seek solutions to key challenges by combining measures addressing all the work system elements; that is the organization, the work environment, the tasks, the tools and technology and the remote operator.

Keywords: Automated transport, remote operation, control room, system design, work-system model.

1. Introduction

Europe faces a shortage of bus drivers (IRU, 2022), as well as a need for cost-efficient and accessible public transport. Automated buses can help address these challenges by reducing the need for staff (Quarles et al., 2020) while also enhancing road safety (European Commission, n.d.). Currently, buses at the Society of Automotive Engineers (SAE) level 4 of driving automation (high driving automation) are piloted in numerous European cities or regions, with safety drivers in the driving seat.

The near-future aim for automated buses is to replace the safety driver with a remote operator who will monitor and assist multiple buses from a control room. Remote operators will perform

tasks that are both time-critical and safety-critical. Consequently, their work organization and the design of interfaces between operators and the automated system must enhance traffic safety and traffic flow.

In this systematic literature review, we map current knowledge on the remote operation of automated buses and on remote operations in comparable domains, focusing on the human role (i.e., the remote operator) and the human-machine interfaces within the remote operation system. While literature on human aspects of remote operation has been reviewed in previous papers (e.g., Blackett et al., 2023; Gontscharow, 2023), our approach provides new insights by systematically mapping the studies according to a

holistic work-system model (Carayon, 2009) and discussing findings and identified research gaps in relation to this model and human-centered systems design literature.

2. Theoretical perspectives

The theoretical foundation of this paper rests on two assertions. First, the design of remote operation functions must actively involve humans whose work creates the safety of the remote operation system. Second, system design should adopt a perspective that integrates multiple elements, such as tools, interfaces, organizational structures, and work processes, into a coherent whole. To support this approach, we draw on principles from human-centered system design and employ a holistic work-system model (Carayon, 2009).

2.1. Systems design

Human-Computer Interaction (HCI) is a multidisciplinary research field focused on the design and use of technology, with emphasis on interfaces between humans and computers (Preece et al., 1994). HCI provides advice applicable to interaction design, for example, that it is conducted in close collaboration with users, takes place in iterations, and involves frequent empirical testing (Preece et al., 2015). HCI emphasizes understanding user needs, tasks, and cognitive processes, offers structured evaluation methods, and provides guidelines for designing for reliability and clear visibility of system statuses, and is, as such, a suitable framework for designing safety-critical interfaces for monitoring and assisting automated buses. Some research on automated transport has been carried out within HCI (e.g., Alsos et al., 2025; Brown et al., 2023), but not research covering the design of interfaces for monitoring automated, road-based transport.

We envisage a future where operators collaboratively monitor and assist fleets of automated buses engaged in public transport. Hence it is necessary to design interfaces that allow operators to work collaboratively. Computer-Supported Cooperative Work (CSCW) is a subfield of HCI concerned with the study of how people use technology collaboratively, often towards a shared goal (Grudin & Poltrock, 2024). CSCW is also concerned with the design of collaborative systems. For instance, Randall et al. (2021) have shown how ethnomethodology can be

used to anchor the design of collaborative tools in workplace practices. Limited examples of CSCW studies in automated transport exist (e.g., Johansen et al., 2024; Lustig, 2019), but neither of these focuses on monitoring and assistance systems for automated road-based transport. However, several CSCW studies have thematized control room work, identifying its time-criticality and, in some contexts, its safety-criticality, and measures to enhance shared situational awareness and close collaboration between operators with adjacent competencies. (cf. Normark et al., 2024).

2.2. The work-system model

Research on the adoption and use of new technologies highlights the need to consider human, social, and organizational dimensions alongside technical infrastructure (e.g., Carlsson et al., 2022; Melberg & Gressgård, 2023). This holistic perspective aligns with classic socio-technical systems theory (Trist & Bamforth, 1951), which advocates the joint optimization of social and technical elements, aiming to ensure that technological innovation is harmonized with human capabilities, team processes, and organizational structures, thereby enhancing safety and effectiveness. Implementing remote operation of automated public transport is hence not just a technical task – it is a challenge that spans technology, human operators, teamwork, and organizational factors (e.g., Andersson & Söderman, 2024; Morin et al., 2024). A key contribution of this paper is to apply a sociotechnical work-system model (Carayon, 2009) to discuss the literature search results.

Carayon's (2009) sociotechnical work-system model includes psychosocial, cognitive, and physical aspects of work, described through the elements technology and tools, tasks, individual characteristics, organization, and environment. As Figure 1 shows, these elements interact in various ways, producing different loads on the individual (Carayon, 2009). Applying the model to the remote operation of automated buses, the 'person' is the remote operator. 'Tools and technology' refer to the hardware and software needed for completing the 'tasks' (monitoring and assisting automated buses). 'Organization' refers to the division of labor, both horizontally (e.g., in teams) and vertically (management levels), and 'environment' refers to the physical work environment. The outcome of processes within this

system is the safe and efficient remote operation of automated buses.

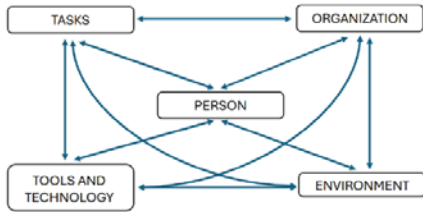


Figure 1. The Work-system model (adapted from Carayon (2009)).

3. Methodology

The review was conducted in accordance with the Preferred Reporting Item for Systematic Reviews (PRISMA) guidelines to ensure transparency and rigor. We aimed to identify and synthesize literature relevant to the design and implementation of remote operation for automated buses in the context specified above. The search was conducted in the research databases IEEE Xplore, Scopus, and TRID, in October 2025. Additionally, we used snowballing to ensure that any relevant studies not identified in these databases could be included.

Our search string combined the concepts remote operation, control room and human-centered design/organization of work: (remote operation OR remote control OR teleoperation OR distance operation) AND (control room OR command center OR operations center OR monitoring station) AND (work organising OR work organizing OR work conduct OR human factors OR user interface OR usability OR user experience OR HCI OR HMI). The same search string was used in all databases.

Studies were relevant if they 1) addressed organizational or work-related aspects of remote operation or control rooms, 2) provided empirical findings, conceptual frameworks, or design recommendations relevant to automated systems, 3) were published between 2015 and 2025, 4) written in English language, and 5) were published in peer-reviewed journals, conference proceedings, or books. Studies were excluded if they 1) focused solely on technical infrastructure aspects, without organizational or human factors considerations, 2) were opinion pieces, editorials, literature reviews, or lacked sufficient methodological detail.

All identified records were imported into a reference management tool, and duplicates were removed. Two reviewers independently screened titles and abstracts against the eligibility criteria. Full text screening was conducted for potentially relevant studies. Screening disagreements were resolved through discussion.

The study selection process is illustrated in Figure 2. A total of 1610 records were identified through database searches. After removing 18 duplicates, 1592 records remained for screening. Titles were reviewed first, and 1484 records were excluded for not meeting the eligibility criteria. 108 abstracts were examined in detail, and 45 full-text articles were assessed for eligibility. One paper was identified through other sources and screened using the same criteria. Following full-text review, 35 articles were excluded for reasons such as being focused on technical infrastructure or lack of relevance to organization of work in remote operations. Ultimately, 10 studies were included in the qualitative synthesis.

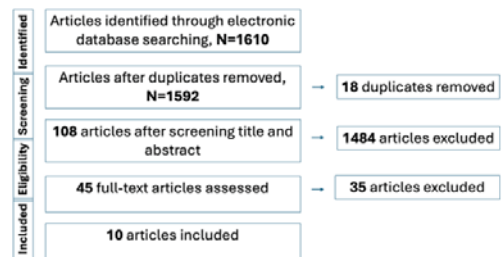


Figure 2. Prisma flow diagram.

4. Results

Like Gontcharow et al. (2023), we note that the literature on remote operations is fragmented. Our review shows that the number of relevant articles is limited. The relevant studies are presented in section 4.1. In section 4.2, we summarize key insights from the studies.

4.1. Overview and summary of relevant studies

An overview of the relevant studies identified in the literature search is presented in Table 1. In column 3, we have applied Carayon’s (2009) work-system model to indicate our understanding of the focus element of the article (in bold) and the interactions between the element in focus and other work-system elements. The interactions presented in Table 1 are illustrated in relation to Carayon’s (2009) model in Figure 3. The numbers

in this figure denote the number of studies focusing on particular elements and interactions.

Table 1. Articles included in the study

Authors and publ. year	Domain	Work system elements and interactions ^a
Braseth et al. (2022)	Maritime	Tools/tech. ↔ tasks, ind.
Buck et al. (2023)	Air (drones)	Tools/tech. ↔ ind., tasks, env.
Cheng et al. (2024)	Maritime	Ind. ↔ Env.
Hurlen et al. (2022)	Petroleum	Tools/tech. ↔ tasks, ind. Org. ↔ tasks, ind.
Johansen & Utne (2024)	Maritime	Tools/tech. ↔ tasks, ind.
Kamboj et al. (2022)	Agriculture	Tasks ↔ tools, ind.
Kumar et al. (2020)	Space	Tasks ↔ tools, ind.
Sumon et al. (2025)	Maritime	Tasks ↔ Tools/tech
Unverricht et al. (2023)	Air (drones)	Tasks ↔ ind., tools/tech., org.
Veitch & Alsos (2024)	Maritime	Task ↔ Ind.

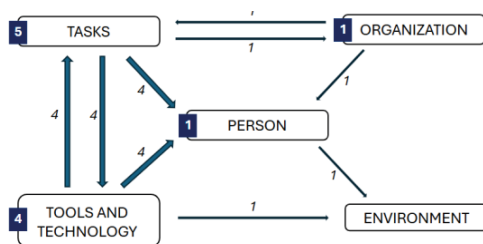


Figure 3. The number of identified studies focusing on particular elements and interactions.

Braseth et al. (2022) focus on remote operators' preferred supervision viewpoints (vessel-centric vs. map-centric) and the type of information available on the displays. The study found that when remotely operating three ships, the majority of the operators (n=8) preferred a map-centric view, with a smaller view of each ship's bridge view on the side of the screen.

Buck et al. (2023) study the setup of workstations and a shared video wall at control rooms overseeing unmanned aerial systems vehicles (drones). The operators involved in the study (n=6) found the suggested setup usable and efficient. The study recommended that displays communicate clear and concise suggestions for how operators can handle a problem (rather than only identify the problem).

Cheng et al. (2024) employ Human Reliability Analysis to identify human errors when monitoring and assisting autonomous vessels, and identify performance-shaping factors in the same context, such as experience, boredom, task complexity, pre-warning, and available time. They find that available time to detect and respond to abnormal events has the greatest influence on success when humans take over control. This is followed by the degree of task complexity (one vessel in light traffic versus three vessels in heavy traffic) and pre-warning (in situations of exceeded operational limits).

Hurlen et al. (2022) discuss the importance of organizational and operational aspects (human factors, team organization, and digital support systems) for managing multiple offshore petroleum facilities from centralized control centers. The paper explores how remote operations can be structured, the importance of competence overlap, and the challenges of coordinating complex, safety-critical activities across facilities. The authors highlight the need for robust communication, clear roles, and adaptive team structures.

Johansen & Utne (2024) introduce a methodology for developing risk-based control systems for autonomous ships, emphasizing collaboration between human supervisors and automated systems. Using Systems Theoretic Process Analysis (STPA) and Bayesian belief network (BBN) modelling, the system notifies human supervisors when intervention is needed and supports safe transitions between automated and manual control. Simulation results demonstrate that such shared control improves operational safety and flexibility.

Kamboj et al. (2022) study how to design audio-based verbal communication interfaces

^a Interactions are indicated with the symbol ↔. The area in focus in each article is indicated in bold.

Abbreviations: Env.=environment; ind.=individual; Org.=organization; Tech.=technology.

between farmers and fleets of small under-canopy robots. Through an experimental study design, they find that single-phrase communication increases both the success of interaction and user satisfaction compared to sentence-based communication and interaction without audio.

Within the space domain, **Kumar et al. (2020)** establish a methodology for assessing the situational awareness and cognitive load of humans who remotely operate construction robots in space. They find that cognitive load is increased in a remote environment, whilst situational awareness is reduced.

Sumon et al. (2025) take a systemic stance and perform a desk-top hazard analysis of a use case short-sea service vessel to identify the most safety-critical control actions associated with different controllers (including the operator located in a remote operation center as one controller, while the others are technological systems). The analysis identifies control tasks performed by remote operators as hazards.

Unverricht et al. (2023) study the behavior of four ground control station operators of uncrewed aerial systems exposed to seven different live flight operations in a natural environment. The study finds that tilt-reflex, expertise, shared situation awareness, and locus of responsibility promote task performance, while complacency, high mental workload, miscalibrated trust, vigilance, and automaticity reduce it. Also, the study finds that trust and familiarity within the team and established review processes of operations, scenarios, and vehicles help mitigate perceived risk.

Within the context of remote operations of autonomous ships, **Veitch & Alsos (2024)** ask: Is remote operating center (ROC) work boring? The study found a drop in vigilance between 5 and 30 minutes in a monitoring task. The 30-minute group experienced a higher degree of boredom, lack of challenges, and reduced meaning. The paper discusses 1) task content, and 2) task structure, pointing to the need for applying an organizational design of ROC that embeds task variation and meaningful work.

4.2. Key insights from reviewed studies

In Table 2, insights from the reviewed studies relevant to the remote operation of automated buses are summarized. The insights are categorized according to the appropriate element

of Carayon’s (2009) work-system model. However, we emphasize that the insights often span more than one element.

Table 2. Key insights relevant to the remote operation of automated buses.

Individual
Situational awareness (SA): Limited SA, particularly the understanding of the automated system’s next action, can increase the experienced workload, whereas familiarity with the operations can decrease the experienced workload (Unverricht et al., 2023). Performance-shaping factors for ROC operators are experience, boredom, task complexity, pre-warning, and available time (Cheng, et al., 2024).
Tasks
Under-stimulation: Remote operator tasks may involve prolonged periods of monitoring, leading to under-stimulation and boredom (Veitch & Alsos, 2024). SA: Maintaining situational awareness and a balanced cognitive load are core challenges associated with remote operator tasks (Cheng et al., 2024; Unverricht et al., 2023; Kumar et al., 2020). Available time: Available time for the detection, diagnosis, and reaction to an abnormal event is identified as the most important performance-shaping factor (when compared to task complexity, pre-warning, and boredom (Cheng et al., 2024). Pre-warning: Adequate pre-warning (when operational limits of the system are exceeded) and low task complexity decrease the remote operator’s takeover time (Cheng et al., 2024). Mode changes: Mode changes (from automation to human assistance or control) are parts of the operational processes that are particularly safety-critical and vulnerable to human error (Sumon et al., 2025; Veitch & Alsos, 2024).
Tools and technology
Transfer of control: Tools should enable smooth and predictable transitions between automated and manual control modes. Clear handover protocols, predictive alerts, and multimodal (visual/auditory) cues are essential to reduce uncertainty and maintain operational safety (Johansen & Utne, 2024). Communication: Interfaces should support concise, structured communication between humans and autonomous systems (Kamboj et al., 2022). SA: Operators supervising multiple autonomous assets benefit from map-centric views supplemented by local perspectives (Braseth et al. 2022). Actionable alerts: Alerts should not only identify problems but also suggest actionable solutions (Buck et al. 2023). Robust support systems: Robust communication

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channels and digital support systems are necessary to facilitate information flow, maintain situational awareness, and enable effective decision-making (Hurlen et al., 2022).
Environment
Usability and performance: Integration and grouping displays with similar operational information into one single display could improve usability and performance (Buck et al., 2023)
Organization
Team structure and roles: Effective remote operations require several operators working in parallel, with a strong emphasis on coordination and cooperation among team members (Buck et al. 2023). Adaptive team structures and clear role definitions are essential for managing complex, safety-critical activities (Hurlen et al., 2022).
Team competence: The presence of co-located teams with overlapping competencies is highlighted as a key organizational asset (Hurlen et al., 2022). This ensures that operators can support each other, share situational understanding, and collectively address emerging challenges.
Trust: Trust and familiarity within the team help mitigate risk perception and foster a safer operational environment (Unverricht et al., 2023).

5. Discussion

In the foreseeable future, the remote human operator will remain crucial for the safe operation of automated buses. Simultaneously, the involvement of a human operator introduces vulnerability through potential human error and failures in the human-computer interface (e.g., Sumon et al., 2025). Understanding how the operator interacts with automated systems is therefore essential for achieving the reliability and safety that future public transport systems require, and design choices directly influence how effectively hazards are detected and managed.

The studies reviewed for this paper indicate that key remote operator challenges include maintaining situational awareness and vigilance and managing shifts between the passive monitoring of multiple buses and assisting the buses in safety-critical and time-critical situations. As illustrated in Figure 2, most studies focus on the individual remote operator and the connections between the operator and their tasks and tools. However, some studies address how teams of professionals will be involved in remote operator work. Remote operation will require co-located teams and the coordination of team members with similar tasks and competencies

(Buck et al., 2023), as well as a combination of adaptive team structures and clear role definitions (Hurlen et al., 2022).

Several studies focus on the human-computer interface and emphasize the need to design interfaces that increase operator understanding and performance. This includes the need for concise, structured communication between humans and the automated system (Kamboj et al., 2022) and the need for pre-warning when the operational limits of the system are exceeded (Cheng et al., 2024). Though such measures are important, we argue that possible solutions to mitigate risks involving the remote operator must be sought in the entire work system. Carayon's (2009) work-system model is a reminder that the tasks, tools, environment, and organization in work-life are interconnected and interdependent. It is hence essential to consider cross-element interactions, as challenges may appear at one level but require solutions at another. For example, individual-level issues like cognitive fatigue or disengagement may be best addressed through organizational changes such as adjusted work schedules or job rotation. A key question that illustrates this dynamic is how to keep remote operators engaged during idle periods without overwhelming them during hectic ones. Though rooted in individual experience, its resolution may lie in thoughtful task allocation and work organization. Similarly, increasing the number of buses per operator (a task-level change) may demand new decision-support tools and organizational adjustments like enhanced training or shorter shifts. A holistic approach that considers these interdependencies is critical for developing resilient remote operation systems.

The near-future shift from simulation experiments and limited testing of the remote operation of single automated buses to the daily, remote operation of multiple automated buses calls for research that captures the complexities of remote operator work. We recommend that future research examine the challenges of remote operations through studies of the actual work processes of remote operators, involving, for instance, the complexity of supervising multiple buses and potential additional tasks like passenger communication.

Remote operation challenges underscore the need for user involvement to ensure that interfaces, workflows, and control room layouts

match operators' cognitive and collaborative demands. HCI provides methods for studying operator practices and involving them in system design, offering principles for managing attention, making autonomous behavior intelligible, and supporting clear transition between automation and human control. Complementing this, CSCW contributes insights into how shared displays, communication channels, and spatial arrangements sustain joint situational awareness and coordination in time-critical situations. Integrating HCI, CSCW and Carayon's sociotechnical model therefore provides a comprehensive foundation for designing remote monitoring systems, combining user-centered interfaces that minimize cognitive load, collaborative environments that support team performance, and a system-level perspective that aligns individual, task, technological, organizational, and environmental factors to enhance safety and effectiveness.

This system perspective should, however, be complemented by a broader view of the sociotechnical ecosystem in which remote public transport operates. This includes not only control room operators but also fleet managers, public transport authorities, passengers, emergency services, and other stakeholders whose roles and interactions must be considered in system design.

Concerning methodological limitations and transferability, the evidence base in our collected material is heterogeneous and dominated by laboratory-based experimental and simulation studies with small N, which constrains the generalizability of our findings. Most of the studies originate from the maritime and air domains, which require careful transfer to the domain of automated, road-based transport. These findings could be related to the technological maturity level of mass automated transport. While the confidence level is moderate, some findings appear consistent across the domains – related to SA, boredom, and mode transitions – our studies underscore the need for both user-centered design studies, followed by empirical validation in real-world ROCs for automated buses.

6. Conclusion

The systematic literature review conducted for this study shows that relatively few studies on the remote operation of automated buses and on remote operation in comparable domains have

been carried out to date. Though the reviewed studies contribute, among others, important experimental knowledge on the remote operator's tasks, situational awareness, and cognitive load, and on measures enhancing remote operator performance, the next generation of studies within automated bus transport should involve remote operators monitoring and assisting buses (for the time being, with an onboard safety driver taking control if needed) in ordinary work shifts and from real control rooms. Furthermore, to meet the complexities and challenges of remote operations, we advise that further development builds on user involvement and on systemic approaches.

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