Deliverable 2.7

Data gathering and analysis of safety relevant communication in the railway system with special consideration of human factors using the example of the digitalcommand

Project acronym	**PhDs EU-Rail**
Starting date	**1 October 2024**
Duration (in months)	**36 Months**
Call (part) identifier	**HORIZON-JU-ER-2023-01**
Grant agreement no	**101175856**
Due date of deliverable	**31/03/2026**
Actual submission date	**31/03/2026**
Responsible/Author	**Bekir Arslan (Technische Universität Berlin)**
Dissemination level	**Public**

Document history		
Revision	*Date*	*Description*
1	13/03/2026	First draft
2nd Version	25/03/2026	Revised version after peer review
3rd	17/06/2026	Revised version addressing ERJU feedback

Report contributors		
Name	**Beneficiary**	**Details of contribution**
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Executive Summary

The present deliverable provides a comprehensive state-of-the-art review on human factors in digital command and control systems within railway operations, with a specific focus on the transition from traditional written commands to digital command systems in Germany.

As digitalisation transforms safety-critical communication between dispatchers and train drivers, new challenges related to usability, cognitive workload, and operational acceptance emerge. The traditional written command procedure, defined in DB Guideline 408, relies on structured verbal dictation and repetition to ensure high levels of safety and redundancy. In contrast, the digital command system, introduced voluntarily across Germany with the timetable change on 14 December 2025, transmits commands electronically via a central infrastructure, thereby eliminating verbal repetition and accelerating the transmission process.

While this shift promises increased efficiency, standardisation, and documentation, it also alters the verification logic of correct understanding and shifts cognitive demands from auditory-verbal processing to visual-cognitive interaction with technical interfaces.

Preliminary exploratory interviews with train drivers and an analysis of real operational command data from DB Cargo over three years indicate that certain command types, particularly Command 12 regarding temporary speed restrictions, occur far more frequently than others, which has direct implications for interface design. From a human factors perspective, key challenges include maintaining comprehensibility under operational stress, compensating for the loss of verbal redundancy, ensuring trust in digital acknowledgement mechanisms, and managing the coexistence of written and digital procedures during transition phases.

To address these challenges systematically, a methodological framework combining semi-structured interviews, questionnaire-based surveys using standardised instruments such as the System Usability Scale, simulator-based experiments at Technische Universität Berlin, task and process analyses, thinking-aloud techniques, and prototype-oriented feedback sessions has been developed.

The planned empirical research is structured in multiple stages, beginning with interviews of dispatchers and train drivers, followed by a broad questionnaire survey, controlled simulator experiments comparing written and digital command procedures, and complementary observations in real operational environments. The overarching research questions examine how digital commands affect safety-critical communication, cognitive workload, situational awareness, usability, and user acceptance. Ultimately, this research aims to derive human factors requirements for the design and implementation of digital command systems that support both operational efficiency and the high safety standards of railway operations. The findings will contribute not only to the specific case of command digitalisation in Germany but also to the broader discussion on integrating technological innovation with human factors in railway digitalisation processes across Europe.

Abbreviations and acronyms

Abbreviation / Acronym	Description
ARAMIS	Advanced Railway Automation Management & Information System
CFL	Société Nationale des Chemins de Fer Luxembourgeois
CPDLC	Controller Pilot Data Link Communications
DB	Deutsche Bahn
ETCS	European Train Control System
EU	European Union
GMDSS	Global Maritime Distress and Safety System
ÖBB	Österreichische Bundesbahn
SUS	System Usability Scale
TSI OPE	Technical Specifications for Interoperability – Operation and Traffic Management
ZFM	Zugfahrt Management

1 Objective/Aim

The objective of this deliverable is to present the state of the art related to human factors in digital command systems within railway operations. The chapter focuses on safety-critical communication between dispatchers and train drivers and examines the transition from traditional written commands to digital command systems in Germany. Particular attention is given to usability, cognitive workload, and operational acceptance of digital command procedures.

2 Background

The ongoing digitalisation of railway operations introduces new technologies that transform the way operational communication is conducted. One example is the digital command system, which aims to replace or complement traditional written command procedures used in degraded operational situations. While the traditional procedure relies on structured verbal communication between dispatchers and train drivers, digital systems introduce interface-based communication through technical devices. This transition raises new questions regarding usability, cognitive workload, and safety-critical communication. Therefore, a human factors perspective is required to understand how digital command systems influence operational practice and how they can be implemented safely and effectively.

3 Human Factors in Digital Command and Control Systems

3.1 Introduction

Safe communication is a central element of railway operations and forms the backbone of reliable and secure train traffic management. Especially in situations where standard procedures are disrupted—such as signal failures, construction works, or technical malfunctions—a structured and error-free exchange between the involved operational units is of essential importance. In such cases, the so-called "Command" (order) serves as a formalized act of communication that enables deviations from regular operations to be handled safely. (Bekir Arslan "From written to digital commands in german railway operations: challenges and opportunities" (2026))

With the ongoing digitalization of the railway sector, not only are the technical frameworks changing, but so too is the nature of communication itself. Systems such as the European Train Control System (ETCS)—particularly in higher levels that operate without conventional light signals—introduce new requirements for communication between dispatchers and train drivers. At the same time, digitalization opens up new possibilities for transmitting written commands no longer via paper but through secure digital channels. With the timetable change on 14 December 2025, the voluntary use of the digital command was introduced across Germany. (Bjorn Norwig et al. "Der Digitale Befehl, (2023))

3.2 The written command

In German railway operations, written operational commands represent an established procedure to ensure safe train movements in exceptional operational situations. The procedure is defined in DB Guideline 408 and is typically applied when regular operating conditions cannot be maintained, for example due to signal failures, construction works, or technical malfunctions. The written command is prepared by the dispatcher and transmitted to the train driver through a standardized radio communication procedure. During this process, the train driver writes down the command on an official command form while the dispatcher dictates its content. To prevent misunderstandings, the driver must repeat the command verbatim after writing it down. Only after the content has been correctly repeated and the time and date have been confirmed does the command become valid. The command form contains a set of standardized operational commands covering different operational situations, such as passing a signal at danger, operating on an occupied track, or proceeding under restricted conditions. This standardized structure ensures that communication between operational staff remains clear and unambiguous even under time pressure. With the timetable change on 14 December 2025, a revised command form was introduced in Germany. The updated structure was adapted to better align with the European Technical Specification for Interoperability relating to Operation and Traffic Management (TSI OPE). The aim of this adaptation is to bring the national command system closer to European operational standards and to support a more harmonised approach to safety-critical railway communication across the European railway network. As part of this revision, the structure of the command form was reorganised, and certain elements were restructured in order to improve clarity and usability. At the same time, the fundamental principle of the command procedure, namely the safe transmission of operational instructions between dispatchers and train drivers, remains unchanged. (Huth, J. "Fahrdienstvorschrift" (2025))

3.3 The digital command

3.3.1 Digital command in Germany

With the introduction of the digital command, parts of this process are being digitalised. Instead of creating the command exclusively on paper and dictating it via radio communication, the dispatcher can create the command through a digital interface and transmit it electronically to the train driver's device. The command message is generated through a digital system and made available via a central infrastructure. The train driver receives a notification via the train radio system and can then access the command using a suitable device. After confirmation of the train's position, the command becomes visible and must be read and acknowledged by the driver. Compared to the traditional procedure, several steps of the radio communication process are no longer necessary. In particular, the dictation and verbal repetition of the command can be avoided. As a result, the transmission process can be accelerated and the workload for both dispatchers and train drivers may be reduced. At the same time, however, the digitalisation of the command procedure also changes the structure of safety-critical communication. While the written command relies heavily on verbal interaction between dispatcher and train driver, parts of the communication in the digital command procedure take place through a technical user interface. This shift may introduce new requirements for system design and for the interaction between humans and digital systems. (Björn Norwig "Betriebserprobung – Digitaler Befehl. Deutsche Bahn Betriebserprobung "(2025))

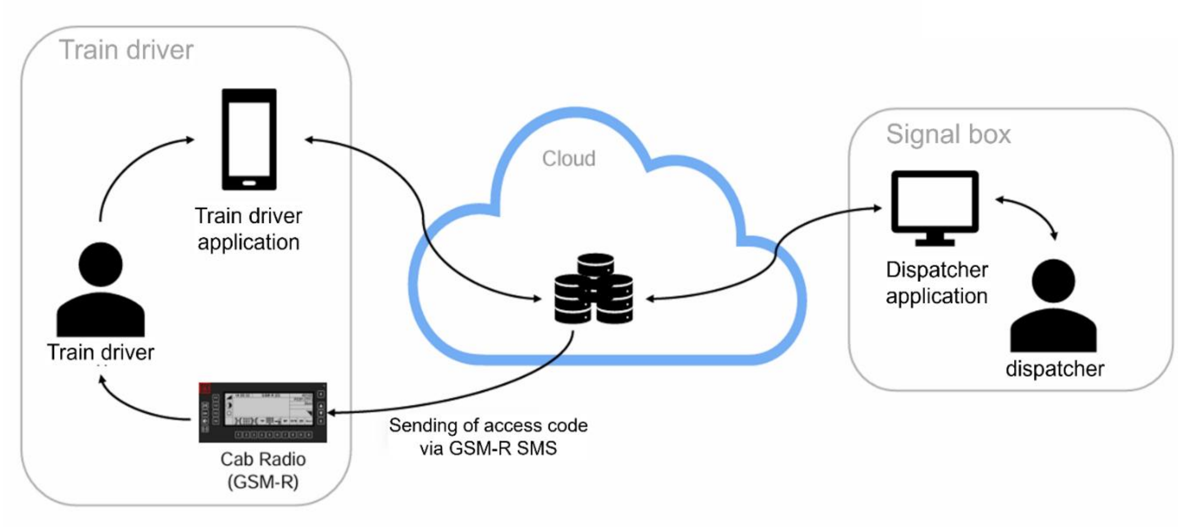

Figure 1: Sequence digital command (Björn Norwig et al. "Der digitale Befehl" (2023))

3.3.2 Digital command in EU

Austria provides a relevant comparison through the implementation of electronic commands within the framework of ÖBB-Infrastruktur AG electronic train movement management system. In this approach, digital commands are not treated as a fully isolated application, but are integrated into a broader digital environment for train-relevant information, including timetable documents, speed restrictions and operational information. The infraDOAS application further supports the integration of operational information into the driver´s cab. (ÖBB-Infrastruktur AG, n.d.)

The Swedish Transport Administration uses a Driver´s order system to convey safety orders to train drivers. Drivers can access orders manually via a website or, for train orders, through a computer-to-computer web service. The system defines clear responsibilities: the infrastructure manager is responsible for the correctness of the information at the point of delivery, while railway undertakings must ensure that orders are conveyed to drivers unchanged and securely archived. (Trafikverket, 2026)

Luxembourg illustrates a different implementation pathway. CFL uses ARAMIS as an integrated real-time traffic management and operational information system. ARAMIS processes information such as train positions, and provides operational views that support traffic management and operational decision-making. Nevertheless, the Luxembourg example also contributes to the broader digitalisation of railway operations, as it illustrates how safety-relevant operational information can be integrated into a digital traffic management environment. (CFL, n.d.)

At European level, TSI OPE and the further deployment of ETCS provide an important harmonisation framework for operational rules, train control and safety-related railway processes. However, they do not currently define a fully harmonised European digital command system. The examples from Austria, Sweden and Luxembourg show that each country follows its own strategy and concept for the digital transmission and integration of safety-relevant operational information. National operational rules, infrastructure conditions, technical systems and implementation strategies still differ considerably. A uniform digital command system across Europe is therefore unlikely to emerge in the short term. For this reason, digital command systems should be analysed both in relation to European standardisation efforts and in comparison, with different national implementation paths.

3.4 Preliminary Insights from Operational Practice

3.4.1 Exploratory interviews with train drivers

Prior to the start of the present research project, initial exploratory interviews were conducted with train drivers in the context of a previous thesis examining the operational implications of digital train commands. These interviews are used as preliminary exploratory input and do not represent the main empirical data collection of the PhD project. The aim of these interviews was to gain first insights into the practical use of operational commands, typical communication procedures, and the perceived advantages and disadvantages of the digital command system. The interviews followed a semi-structured format and addressed topics such as the frequency of command usage, the most common command types, the typical duration of command transmission, and the expected impact of digital command systems on daily railway operations. Additional questions focused on user expectations regarding the future implementation of the digital command system and potential changes to the work processes of train drivers. The results of these interviews provided valuable initial insights into operational workflows and highlighted several aspects that are particularly relevant for further research. Among these are the time required for command transmission, the potential for misunderstandings during radio communication, and the perceived advantages of digital systems in terms of standardisation and documentation. These exploratory findings served as an initial basis for the design of the empirical research planned within the PhD project.

3.4.2 Analysis of command frequency in operational practice

In addition to the exploratory interviews, an analysis of real operational command data was conducted. For this purpose, a set of written commands issued to a train driver of DB Cargo over a period of approximately three years was analysed. The collected commands were categorised according to their command number and evaluated with regard to their frequency of occurrence. This analysis provides an initial indication of which command types occur most frequently in practical railway operations and therefore may be particularly relevant for the design of digital command systems. The results show that certain command types occur significantly more often than others. In the analysed dataset, Command 12 which typically relates to temporary speed restrictions deviating from the electronic timetable (EBuLa) occurred most frequently. Other commands appeared considerably less often, indicating that operational command usage is strongly dominated by a small number of recurring situations. Such insights are relevant for the design of digital command interfaces, as frequently used commands should be easily accessible and clearly represented within the user interface. The dataset is therefore used only to support scenario selection and the methodological preparation of the planned empirical studies. It is not used to derive statistically generalisable conclusions about the overall frequency or distribution of written commands in german railway operations. (W. S. Symang, "Bestimmung möglicher Zeitgewinne im Bahnbetrieb und Betrachtung der sicherheitskritischen Kommunikation durch die Einführung des digitalen Befehls. Bachelor Thesis" (2025))

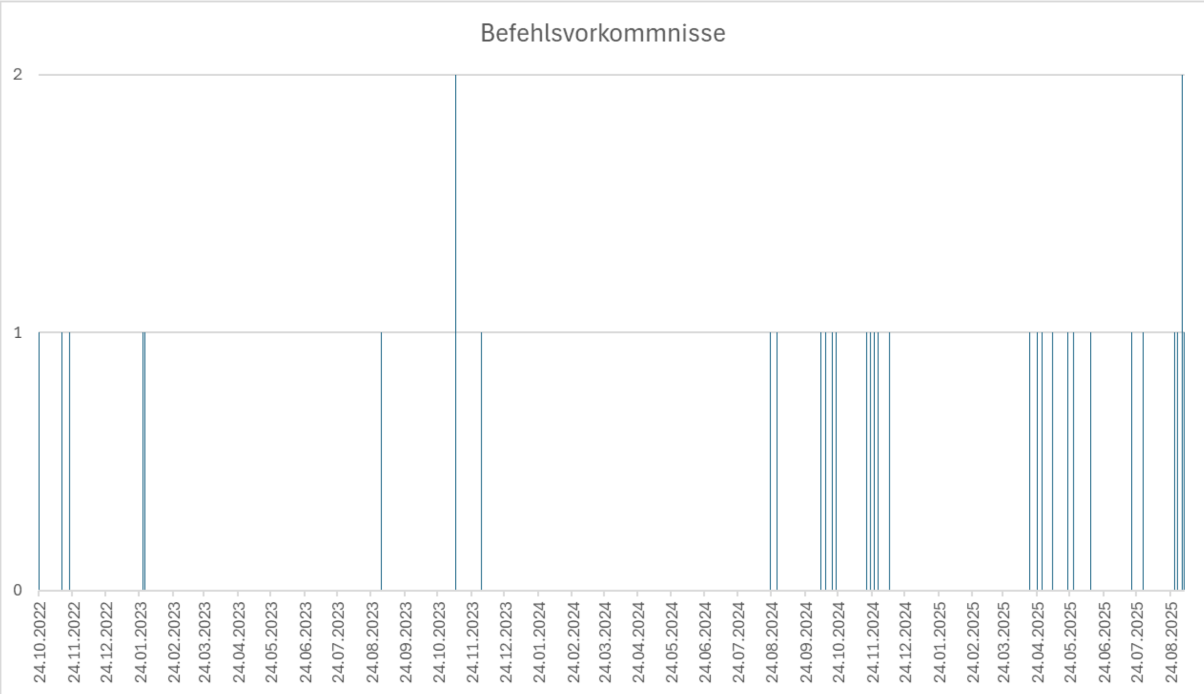

Figure 2: Frequency of operational commands (W. S. Symang, "Bestimmung möglicher Zeitgewinne im Bahnbetrieb und Betrachtung der sicherheitskritischen Kommunikation durch die Einführung des digitalen Befehls. Bachelor Thesis" (2025))

3.4.3 Initial observations on operational workflows

Beyond the quantitative analysis of command frequency, several qualitative observations emerged from the interviews and discussions with operational staff. One frequently mentioned aspect concerns the time required for transmitting written commands. The traditional command procedure requires the dispatcher to dictate the command over the radio, while the train driver writes it down and subsequently repeats it word by word. This closed-loop communication ensures a high level of safety but also requires several communication steps. From an operational perspective, this process can become time-consuming, particularly in situations where multiple trains are affected by the same operational disruption. In such cases, dispatchers must repeat the command procedure for each individual train. Digital command systems promise potential improvements in this regard, as commands can be generated using predefined templates and transmitted electronically without the need for verbal dictation and repetition. At the same time, operational staff emphasised that the established written command procedure has proven to be highly robust and reliable over decades of railway operation. These observations underline the importance of carefully evaluating the impact of digital command systems not only from a technical perspective but also with regard to human factors and operational workflows. The analysed dataset consists of written commands collected from a single train driver over a period of approximately three years. The dataset includes a limited number of operational commands, which were categorised according to their type and frequency. While the dataset provides valuable insights into operational practice, it is not statistically representative and is therefore used as an exploratory data source. (Bekir Arslan "From written to digital commands in german railway operations: challenges and opportunities" (2026))

3.4.4 Cross-domain perspective on safety-critical digital communication

In addition to the European railway perspective, relevant lessons can be drawn from other safety-critical transport domains, particularly aviation, maritime operations and automotive automation. A close cross-domain reference is Controller Pilot Data Link Communications (CPDLC) in aviation. CPDLC enables two-way digital message exchange between air traffic controllers and pilots and can be used as an alternative or supplement to voice communication for standardised messages, clearances, instructions and operational information (SKYbary, n.d.; Smailes et al., 2021; Gurtov et al., 2018). This is highly relevant for digital railway commands, because both systems shift parts of safety-relevant communication from verbal exchange to structured digital message transmission. In both cases, digital messages must be clearly structured, correctly understood, acknowledged and traceable. At the same time, aviation research shows that digital data-link communication creates new challenges related to message presentation, human-machine interface design, authentication, system availability, latency and operator situation awareness (Lehto et al., 2021).

The maritime domain provides further insights through the Global Maritime Distress and Safety System (GMDSS) and e-Navigation initiatives. These systems aim to improve reliable communication, data exchange, distress coordination and interoperability between legacy and modern digital communication channels (Ilcev, 2020; Korcz, 2019; Korcz, 2023). This is relevant for railway digital commands because written, verbal and digital procedures may coexist during transition phases and must remain interoperable. Automotive automation provides an additional perspective on human interaction with increasingly automated systems. Research on automation highlights the importance of trust, mode awareness, transparency and appropriate human reliance on technical systems (Lee & See, 2004; Sarter & Woods, 1995). Although railway operations differ from aviation, maritime and automotive environments, these domains show that digitalisation does not automatically reduce operational risk or workload. Instead, it shifts safety requirements towards reliable message transmission, secure acknowledgement, clear interface design, fallback procedures and the operator's ability to understand and verify digital information under operational pressure.

3.5 Human Factors Perspective and Methodological Framework

3.5.1 Human factors concepts for the evaluation of digital command systems

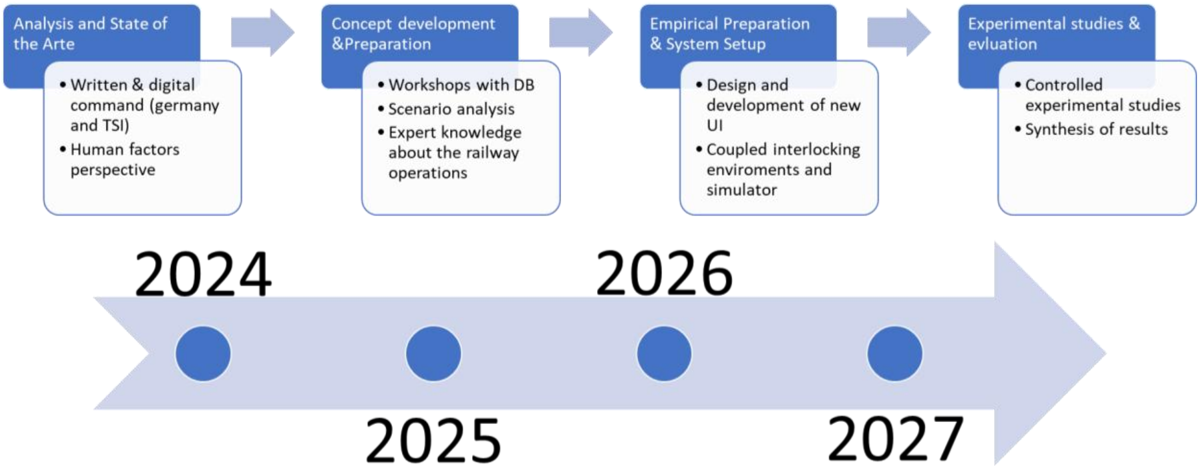

Figure 3: Research process for the evaluation of digital command systems in railway operations.

The evaluation of digital command systems requires a broader literature basis than railway operational rules alone. While national regulations and operational documents define the formal command procedures, the safe implementation of digital command systems also depends on established human factors concepts from safety-critical socio-technical systems (Badke-Schaub et al., 2012). Central concepts for this research include situation awareness, cognitive workload, usability, trust in automation and human-automation interaction. Situation awareness is relevant because train drivers and dispatchers must correctly perceive, understand and anticipate the operational consequences of a digital command. Workload is relevant because digital commands may reduce verbal communication steps, but may also shift cognitive demands towards visual information processing, interface interaction and verification. Usability is important because a technically correct digital command system can still introduce safety risks if information is not clearly structured or if the acknowledgement process is ambiguous. Trust in automation and human-automation interaction are also relevant because digital command systems change the interaction between operational staff, procedures and technical systems. The extended literature basis therefore supports the analysis of the digital command as part of a socio-technical system and not only as a technical transmission tool.

3.5.2 Human factors relevance in digital command systems

From a human factors perspective, this transformation raises several important questions. First, the digital command system must support comprehensibility under operational stress. Dispatchers and train drivers often work under time pressure, in disrupted situations, and in environments with high cognitive demands. In such contexts, even small usability problems may lead to delays, incorrect acknowledgements, or misinterpretations. Second, the replacement of verbal repetition with digital acknowledgement changes how understanding is externally verified. A verbal repetition provides an observable indication that the message content has been processed correctly, whereas a digital acknowledgement may only confirm that a button has been pressed. This creates a different type of verification logic and requires careful evaluation. A further challenge arises from hybrid operational environments in which written and digital command procedures coexist. During the early rollout phase, personnel may have to switch between different communication modes depending on route, infrastructure, operational context, or local practice. Such switching processes may increase cognitive workload and reduce routine-based safety. They may also create uncertainty regarding which procedure is to be used in a given situation and how digital and traditional communication practices interact in everyday operation. In addition, acceptance plays a major role. Even if a digital system is technically functional, its benefits cannot unfold if operational staff do not trust it, do not use it consistently, or perceive it as an additional burden. Factors such as prior experience, habits developed through years of written-command use, perceived reliability, and the quality of training are likely to influence the acceptance of digital commands. In safety-critical contexts, acceptance is not merely a matter of convenience; it directly affects whether a system is used in a stable and predictable way. For these reasons, digital command systems cannot be evaluated solely in terms of technical functionality or nominal process speed. Their implementation must also be assessed with regard to usability, cognitive workload, communication quality, trust, and error susceptibility. A human factors perspective is therefore essential to ensure that digitalisation improves railway operations without weakening the established safety culture. The transition from verbal and written commands to digital systems presents significant challenges for both train drivers and dispatchers. To ensure a safe and smooth transition, it is essential that the user interface be intuitive, that information be clearly presented, and that the cognitive workload remains manageable under operational stress.

3.5.3 Key human factors challenges

Based on the current literature and on the conceptual work already published within the project context, several key human factors challenges can be identified. These findings indicate that the transition to digital command systems does not simply reduce workload but fundamentally transforms the nature of cognitive demands. While traditional procedures rely on distributed cognitive processing through structured verbal interaction, digital systems shift this process towards interface-based interpretation and decision-making. This shift introduces new risks related to misinterpretation, reduced redundancy, and overreliance on system confirmations. Therefore, the design of digital command systems must ensure that efficiency gains do not compromise the robustness of safety-critical communication.

Cognitive workload and information processing

Railway commands are typically issued in degraded or disrupted operational situations. This means that users are already dealing with increased complexity before the command itself is received. In the written procedure, the structure of the dialogue distributes the cognitive process over several steps: listening, writing, repeating, confirming. In the digital procedure, the command may be displayed in a more compact and visually structured form, but this does not automatically reduce workload. Instead, workload may shift from auditory-verbal processing to visual-cognitive processing. Users must navigate interfaces, identify relevant fields, interpret the displayed content, and decide whether the message has been fully understood before acknowledging it. Under time pressure, this may create new forms of mental strain.

Loss of verbal redundancy

The traditional written command relies strongly on redundancy. The command is spoken, written, repeated, corrected if necessary, and only then confirmed. This redundancy is time-consuming but highly protective against misunderstandings. Digital commands reduce this redundancy in favour of efficiency. While this can be beneficial operationally, it also means that fewer natural checkpoints are embedded in the communication process. The question is therefore not whether redundancy is good or bad, but which types of redundancy are still necessary in a digital environment and how they can be replaced or redesigned without overloading the user.

Interface usability and acknowledgement logic

Operational staff have long experience with written command procedures. These routines are deeply embedded in railway practice and are associated with a high level of perceived safety. The introduction of a digital alternative may therefore trigger scepticism, especially if users perceive the system as technically fragile, operationally inconsistent, or insufficiently aligned with real workflows. Trust in digital acknowledgement mechanisms is especially important, because users must believe that the system reliably represents and documents what has been understood and confirmed. If trust is low, personnel may fall back to informal verbal clarifications or avoid the digital procedure wherever possible.

Transition between systems

A particularly relevant challenge in Germany is the coexistence of revised written command procedures and the digital command system. Since the timetable change on 14 December 2025, the voluntary use of the digital command has been introduced, while written procedures remain in place as a parallel and necessary operational fallback. This creates transition environments in which dispatchers and train drivers must potentially alternate between different communication logics. Such alternation may not only increase workload but also produce inconsistent usage patterns and reduce the stabilising effect of routine.

3.5.4 Methodological framework for evaluation

The selected methodological approach is designed to address the research questions from both subjective and objective perspectives. Each method contributes to a specific aspect of the investigation. Semi-structured interviews are used to capture user experiences, expectations, and acceptance of digital command systems. Simulator-based experiments allow for controlled evaluation of workload, errors, and interaction patterns under realistic operational conditions (Badke-Schaub et al., 2012). Questionnaires enable systematic comparison across users, while task and process analyses help to identify cognitive demands within the command procedure. The combination of these methods ensures a comprehensive evaluation of human–system interaction in safety-critical railway communication. To address these challenges systematically, a human factor–oriented methodological framework has been developed and published in recent work by Arslan and Milius. This framework combines qualitative and quantitative methods and is specifically designed for the early deployment and transition phases of digital command systems. Rather than focusing only on technical performance indicators, it aims to capture how dispatchers and train drivers interact with the system, how they understand and acknowledge commands, and which usability or safety issues emerge under realistic operating conditions. The framework consists of several complementary methodological elements. (Stanton et al. “Human Factors Methods A Practical Guide for Engineering and Design “(2016))

Simulator based studies

A central component is the use of simulator-based evaluations. At Technische Universität Berlin, the available laboratory environment combines interlocking technology with a train driving simulator. This makes it possible to reproduce realistic operational scenarios and to examine command transmission and acknowledgement under controlled but practice-oriented conditions. Both the existing Deutsche Bahn digital command system and alternative prototype concepts can be integrated into this environment. This allows direct comparison between different interface designs and operational procedures. Simulator-based studies are particularly suitable because they allow systematic variation of relevant factors such as time pressure, scenario complexity, and command type, while keeping the broader experimental context stable. They also provide a safe environment for testing potentially problematic situations that would be difficult or risky to analyse in real operations. The simulator studies at TUB will integrate workload, stress and operational realism by using realistic disruption scenarios in which written or digital commands are required. These scenarios may include signal failures, temporary speed restrictions, route deviations or situations in which several trains are affected by the same operational constraint. Workload will be varied through scenario complexity, the number of information elements, time pressure and the need to switch between written and digital procedures. Stress will not be induced artificially, but through realistic operational constraints such as limited decision time, disrupted traffic conditions and simultaneous information processing. The evaluation will combine objective indicators such as task completion time, errors, clarification needs and interaction steps with subjective measures such as SUS, workload ratings, think-aloud protocols and structured debriefings. (Stanton et al. "Human Factors Methods A Practical Guide for Engineering and Design "(2016))

Task analysis and process analysis

In addition to simulation, task and process analyses are used to understand how the command procedure is structured from the user perspective. This includes identifying individual action steps, decision points, sources of uncertainty, and moments of high attentional demand. By comparing written and digital command procedures on this level, it becomes possible to identify where workload is reduced, where it is merely shifted, and where new forms of interaction risk may arise. (Stanton et al. "Human Factors Methods A Practical Guide for Engineering and Design "(2016))

Semi-structured interviews

Semi-structured interviews with dispatchers and train drivers form another important component. They are used both after simulator sessions and in relation to operational rollout. Their purpose is to capture subjective assessments of comprehensibility, usefulness, trust, acceptance, and perceived safety. Interviews also allow users to describe situations that they found confusing, stressful, or particularly well supported. This is important because many human factors issues are not directly observable through performance data alone but become visible only when users reflect on their experience. (Stanton et al. "Human Factors Methods A Practical Guide for Engineering and Design "(2016))

Questionnaires and standardised usability measures

Questionnaires complement the interviews by enabling more systematic and comparable measurement. Likert-scale items can be used to assess acceptance, perceived usefulness, or workload-related dimensions, while standardised instruments such as the System Usability Scale (SUS) provide a recognised baseline for usability evaluation. In addition, the project context already foresees the use of metrics such as workload assessments and communication-related measures. Together, these instruments allow comparisons across user groups, systems, and phases of implementation. (Stanton et al. "Human Factors Methods A Practical Guide for Engineering and Design "(2016))

Thinking-aloud techniques and debriefings

Thinking-aloud techniques are especially useful during simulator studies and prototype tests. They allow participants to verbalise what they are attending to, what they find confusing, and how they interpret particular interface elements while interacting with the system. Combined with structured debriefings after task completion, this method can reveal mismatches between intended system logic and actual user interpretation. (Stanton et al. "Human Factors Methods A Practical Guide for Engineering and Design "(2016))

Mock-ups and prototype-oriented design feedback

Mock-up studies provide a way of collecting early design-oriented feedback even before large-scale system changes are implemented. Participants can be asked to visualise how they expect the digital command interface to support them, which information should be foregrounded, and how command sequences should be structured. This is particularly valuable because it moves beyond mere criticism of the existing system and allows users to contribute constructively to design improvements. Both published papers emphasise this iterative and user-centred perspective. (Stanton et al. "Human Factors Methods A Practical Guide for Engineering and Design "(2016))

3.5.5 Implications for the present PhD project

The methodological framework developed in the recent publications provides the scientific basis for the present PhD project. It shows that the evaluation of digital command systems must go beyond technical implementation and include the broader socio-technical interaction between users, interfaces, organisational procedures, and safety requirements. For the PhD project, this means that empirical work will not be limited to asking whether digital commands save time. Instead, the research will examine under which conditions they are understandable, trustworthy, usable, and compatible with the cognitive and operational realities of dispatchers and train drivers. Particular attention will be paid to transition phases, route-specific differences, and situations in which written and digital procedures coexist. The framework is also valuable because it is transferable. While it is tailored to the digital command in German railway operations, its logic can also inform the evaluation of other safety-critical digital communication systems in rail transport and related transport domains. In this sense, the project contributes not only to the specific issue of command digitalisation but also to the broader discussion on how technological innovation and human factors must be integrated in railway digitalisation processes. (Badke-Schaub et al. 2012)

4 Discussion and further work

Building on the analysis of the operational context and the identified human factors challenges, the present research aims to investigate the implications of digital train commands for safety-critical communication processes in railway operations. In particular, the study focuses on how the digitalisation of command procedures affects operational workflows, information processing, and user acceptance among railway staff. While digital command systems promise advantages such as increased efficiency, standardisation, and improved documentation, their impact on the interaction between dispatchers, train drivers, and technical systems has not yet been comprehensively investigated. In particular, the shift from verbal communication to interface-based interaction raises new questions regarding usability, cognitive workload, and the verification of correct understanding. Against this background, the research addresses the following key research questions:

1. How does the introduction of digital train commands affect safety-critical communication between dispatchers and train drivers?
2. What impact do digital command systems have on cognitive workload, situational awareness, and information processing among operational staff?
3. Which usability challenges arise when digital command systems are used in real operational contexts?
4. How do dispatchers and train drivers perceive digital command systems, and which factors influence their acceptance?
5. Which human factors requirements can be derived for the design and implementation of digital command systems in railway operations?

Answering these research questions will contribute to a better understanding of the interaction between digital technologies, human cognition, and operational safety within railway systems.

4.1 Planned empirical studies

The following empirical investigations are planned as part of the PhD project and build upon the preliminary insights described above. To address the research questions, a multi-stage empirical research design is adopted, combining qualitative and quantitative methods. The aim is to capture both subjective user experiences and objective aspects of system interaction. At the current stage of the project, no new empirical interview, questionnaire or simulator data have yet been collected within the PhD study. The following sample design therefore describes the planned empirical phase. The main target groups are train drivers and dispatchers, as these two roles are directly involved in the command communication process. The final sample size will depend on operational availability and access to railway staff. The study will aim to include participants with different levels of professional experience, age groups, digital experience and, where feasible, gender diversity. Since the railway operational workforce is not evenly distributed across gender groups, the final sample composition will be documented transparently and considered in the interpretation of the results.

Table 1: Planned empirical sample design and analysis approach

Method	Target group	Planned sample size	Main purpose	Planned analysis
Semi-structured interviews	Train drivers and dispatchers	Approx. 20-50 participants	Identify practical experiences, user requirements, communication	Qualitative content analysis

			challenges and safety-relevant issues	
Questionnaire	Train drivers and dispatchers	Approx. 60-100 participants	Assess usability, acceptance, perceived safety, workload, trust and error proneness	Descriptive statistics, scale analysis and exploratory group comparisons
Simulator-based experiments	Train drivers, dispatchers and role-based participants	Approx. 24-36 participants	Compare written and digital command procedures under controlled conditions	Task completion time, errors, clarification needs, workdload, usability and debriefing analysis

4.1.1 Interviews with operational staff

The first step of the empirical investigation involves conducting semi-structured interviews with dispatchers and train drivers. These interviews aim to provide insights into practical experiences with command procedures, expectations regarding digital systems, and perceived challenges in everyday railway operations.

Particular attention will be given to the following aspects:

- comprehensibility of digital commands
- changes in communication processes
- perceived advantages and disadvantages
- trust in the system and perceived reliability

The results of these interviews will also serve as a basis for the development of further research instruments, such as questionnaires and experimental scenarios.

4.1.2 Questionnaire-based survey

Building on the results of the interviews, a structured questionnaire will be developed and distributed among train drivers and dispatchers. The objective of this survey is to systematically collect data on several aspects of digital command usage.

The questionnaire will address topics such as:

- perceived usability of digital command systems
- perceived workload during command handling
- perceived safety and reliability
- overall acceptance of the system

Standardised usability assessment methods, such as the **System Usability Scale (SUS)**, may be used to evaluate the usability of the system. In addition, Likert-scale questions will allow the quantitative assessment of user perceptions and attitudes.

4.1.3 Simulator-based experiments

Simulator-based experiments represent a central element of the empirical investigation. At the Railway Operations and Infrastructure department of Technische Universität Berlin, laboratory environments are available that include interlocking technology and simulation-based operational environments. Within these experiments, typical operational scenarios in which train commands are issued will be recreated. This allows the comparison of different command procedures, such as traditional written commands and digital commands.

The experiments may analyse several aspects, including:

- time required to process commands
- occurrence of errors or misunderstandings
- interaction patterns between users and systems
- perceived workload during task execution

The simulator environment enables controlled experimental studies without affecting real railway operations.

4.1.4 Observations in operational environments

In addition to experimental studies, observations in operational environments may be conducted, for example in control centres or during cab rides with train drivers. The aim of these observations is to better understand real operational workflows and communication structures. Such observations can help contextualise the findings from simulator experiments and provide additional insights into practical challenges encountered in daily railway operations.

5 Conclusion

Safe communication is a cornerstone of efficient and secure railway operations—whether carried out through traditional written orders or modern digital systems. As new technologies are introduced, it becomes increasingly important to ensure that humans and machines interact effectively and intuitively. Human factors play a central role in this transformation: Only when train drivers and dispatchers fully understand and confidently apply the new procedures can safety and efficiency be maintained. This research project aims to optimize communication workflows, minimize risks, and support the practical implementation of digital command systems within a framework that is both user-centered and safety-oriented. The digitalisation of operational communication processes represents an important element of the ongoing transformation of the railway sector. The digital train command is an example of such innovation, where traditional operational procedures are complemented or partially replaced by digital technologies. While digital commands offer potential advantages in terms of efficiency, standardisation, and documentation, their implementation also changes the structure of safety-critical communication within railway operations. In particular, the shift from verbal communication to digital user interfaces requires careful consideration from a human factors perspective. This deliverable has first described the operational context of train commands in railway operations and identified key challenges related to the introduction of digital command systems. Based on these insights, a methodological framework has been presented to systematically investigate the impact of digital commands on operational practice. The planned empirical studies aim to provide a deeper understanding of the interaction between humans, technology, and organisational processes in the context of digital command systems. In the long term, the findings of this research may contribute to the design and implementation of digital command systems that support both operational efficiency and the high safety requirements of railway operations.

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