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Designing User Interfaces for Semi-Autonomous Tram Systems: Human–Machine Interaction, Future Scenarios, and the Transition Toward Automated Mobility

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ABSTRACT

The increasing adoption of semi-autonomous systems in public transport introduces new challenges for user experience, human–machine interaction and situational awareness. This research, conducted through a design-driven investigation and an intensive workshop involving Master's students in Advanced Sustainable Design at the University of Florence and a leading autonomous tram company, explores how user interfaces can effectively mediate between automation and operator control in complex operational environments. The semi-autonomous tram line of Florence served as a real-world case study to assess current UI limitations and identify opportunities for improvement through UX- and interaction design–oriented approaches. A human-centered methodology structured the process through literature review, benchmarking, field observations, interviews, and questionnaires. Findings reveal recurrent disruptions and highlight the evolving role of the operator, who must manage cognitive load, attention demands, and stress peaks during critical events. The research underscores the need for multimodal feedback—visual, auditory, and tactile—to improve situational awareness, while future concepts envision adaptive dashboards, AI-assisted alerts, and immersive technologies for training and real-time support. The study shows how design can inform the next generation of cooperative, transparent interfaces, enhancing safety, operator comfort, and public trust while supporting the transition toward autonomous urban mobility. In conclusion, the research demonstrates the relevance of design-driven methodologies in shaping the next generation of UIs for semi-autonomous tram systems. By integrating human factors, emerging technologies, and speculative scenarios, the study outlines how adaptive, multimodal, and intelligent interfaces can enhance safety, efficiency, and user comfort, supporting the broader transition toward fully autonomous public transport ecosystems.

Keywords: Human–machine interaction (HMI), Semi-autonomous public transport, Multimodal user interfaces, Adaptive and AI-assisted dashboards, Situational awareness

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INTRODUCTION: THE ROLE OF UX/UI DESIGN IN CONTEMPORARY MOBILITY SYSTEM

Urban mobility is undergoing a phase of profound transformation, driven by the growing demand for efficient, low-emission, and user-centred public transport solutions. Across Europe, cities are progressively reorienting their mobility strategies toward high-capacity collective systems capable of reducing traffic congestion, lowering environmental impact, and improving travel times. Within this scenario, rail-based transport—and in particular tram systems—has re-emerged as a strategic infrastructure for sustainable urban mobility. Trams combine electric propulsion, strong integration within the urban fabric, and infrastructural costs significantly lower than those of light metro systems, making them especially attractive for mid-sized and large metropolitan areas (Laarni & Väätänen, 2023).

In Italy, approximately 250 km of new tram lines are currently under development, representing an estimated 63% expansion of the existing national network and supported by over €5.4 billion in public investment. Within this national framework, the city of Florence is adopted in this paper as a primary geographical and infrastructural case study. With more than 39 million passengers recorded in 2024 and an annual increase of 11.8%, Florence exemplifies the consolidation of tram transport as the backbone of a sustainable mobility strategy. The inauguration of the T2 line extension in January 2025, together with the ongoing development of the T3 and T4 lines scheduled for 2027 and 2028, reflects the city's long-term commitment to public transport innovation and establishes a fertile context for experimentation in automation, energy optimisation, and advanced user services.

Alongside the urban and infrastructural dimension represented by Florence, the paper also adopts an industrial case study perspective, focusing on Hitachi Rail as a leading international company in the design, development, and production of rolling stock, signalling systems, and digital solutions for tram and rail transport. Hitachi Rail operates globally and is actively involved in the development and management of tramway systems, including those currently operating on the Florentine network. This dual focus—urban context and industrial system provider—allows the study to investigate UX/UI design both within a specific geographical setting and within a broader international technological framework.

As tram systems evolve toward semi-autonomous and, in the near future, fully autonomous operation, the design of user interfaces (UIs) and user experiences (UX) becomes a critical factor in ensuring safety, usability, and social acceptance. Hybrid and semi-autonomous tram systems require continuous interaction between human operators and intelligent systems, relying on interfaces capable of mediating complex information flows, supporting decision-making, and maintaining high levels of situational awareness under variable operational conditions.

In this context, UX/UI design assumes a strategic role that extends beyond visual communication or ergonomics, becoming a core infrastructural component that shapes how operators perceive system states, interpret automation behavior, and respond to unexpected events. Well-designed interfaces can reduce cognitive load, minimise stress, and support timely and accurate reactions; conversely, poorly designed interfaces may generate confusion, mistrust, and potentially hazardous situations. The transition toward higher levels of automation therefore necessitates a systemic reconfiguration of interaction models, visual languages, multimodal feedback strategies, and adaptive information architectures (Dong et al., 2024).

At the same time, public transport systems increasingly function as social and communicative devices. As automated mobility becomes part of everyday life, trams—both as physical vehicles and as digital systems—act as cultural mediators that familiarise drivers, technicians, and passengers with new forms of machine intelligence. The hybrid phase currently experienced in cities such as Florence is thus not merely a technological intermediary, but also a communicative and cultural transition zone in which trust, responsibility, and control are progressively negotiated through interface transparency, intelligibility of automation behavior, and clear feedback loops.

For these reasons, this paper frames UX/UI design not as an ancillary layer, but as a foundational component of emerging mobility ecosystems. By integrating human-centred design methodologies, empirical field research, and exploratory design scenarios, the study investigates how interface design can actively contribute to safer, more efficient, and more user-friendly semi-autonomous tram systems. The following sections present the technological background, methodological framework, and empirical findings derived from a design workshop conducted at the University of Florence, illustrating how UX/UI innovation can address the emerging challenges of automated public transport.

STATE OF THE ART OF TECHNOLOGIES IN CONTEMPORARY TRAM SYSTEMS

Understanding the current technological landscape of semi-autonomous tram systems is essential for situating interface redesign within realistic operational constraints. This section outlines the levels of automation currently adopted in Light Rail Transit (LRT), followed by an analysis of Advanced Driver Assistance Systems (ADAS) and Obstacle Detection and Tracking (ODT) technologies. The objective is to clarify system functionalities, identify limitations, and highlight the technological components that directly shape human–machine interaction.

Levels of Automation in Tram Systems

The introduction of autonomous functionalities in urban Light Rail Transit (LRT) represents a significant shift for future smart cities, promising increased efficiency, enhanced safety, and substantial contributions to sustainability goals. Compared with heavy rail or metro systems, however, tram networks present unique challenges: they operate within open, mixed-traffic environments, intersect complex urban layers, and are exposed to unpredictable interactions with pedestrians, cyclists, and private vehicles. These conditions demand high levels of situational awareness and more dynamic forms of human–machine collaboration than those required in fully segregated rail systems.

In the automotive sector, the Society of Automotive Engineers (SAE, 2021) defined a six-level taxonomy of driving automation, ranging from Level 0 (no automation) to Level 5 (full autonomy). While this classification provides a useful conceptual reference, public transport systems adopt a parallel but distinct framework. In this domain, automation is commonly described through the Grade of Automation (GoA) model defined by the International Association of Public Transport (UITP), which distinguishes levels based on the allocation of responsibilities between human operators and automated systems (Guerrieri & Parla, 2022). According to the UITP framework, four main Grades of Automation are identified:

1. **GoA1 – On-board Driver Operation**: the driver performs all driving tasks, supported by Automatic Train Protection (ATP).
2. **GoA2 – Semi-Automatic Train Operation**: the system manages speed and braking through Automatic Train Operation (ATO), while the driver intervenes in case of malfunction and remains responsible for door operations.
3. **GoA3 – Driverless Train Operation**: no driver is present on board; staff intervene only when necessary. Both ATP and ATO are fully active.
4. **GoA4 – Unattended Train Operation**: full automation with no on-board staff.

Inspired by UITP's GoA framework, SYSTRA later proposed a more granular six-level **Levels of Automation (LoA) model,** specifically tailored to Light Rail Transit systems, ranging from fully manual operation to fully autonomous systems without on-board personnel (SYSTRA, 2018). Despite these conceptual advances, the majority of existing tram networks worldwide still operate at GoA1, with limited or no automation

Nevertheless, increasing digitalization—driven by growing demand for service capacity, safety, and operational efficiency—has led to the development of preliminary assisted-driving configurations corresponding to LoA1 and LoA2. These systems integrate sensor-based monitoring, collision assistance, and partial automation features, paving the way for more advanced hybrid and autonomous solutions.

Advanced Driver Assistance Systems (ADAS)

Advanced Driver Assistance Systems (ADAS) were originally developed to improve road safety by preventing accidents and mitigating their severity (Guerrieri & Parla, 2022). Today, they encompass a wide range of functions, including collision warning, collision-avoidance intervention, driving control assistance, and parking support. While widely deployed in automotive contexts, ADAS technologies are increasingly being tested and adapted for semi-autonomous tram systems.

In the context of autonomous and semi-autonomous trams, ADAS plays a crucial role in monitoring complex urban environments, detecting obstacles, and assisting drivers—or automated controllers—in timely decision-making processes. These systems rely on multimodal sensor architectures, typically including:

1. **LiDAR**, for high-precision three-dimensional mapping and distance measurement;
2. **Radar**, ensuring reliable detection under adverse weather conditions;
3. **Cameras**, enabling classification and recognition of pedestrians, cyclists, and vehicles;
4. **Inertial Measurement Units** (**IMU**), providing inertial data to enhance stability control and trajectory estimation.

One of the primary challenges in tram operation is the high incidence of collisions with pedestrians or vehicles, as well as the frequent presence of unexpected obstacles along the tracks. With over 7,000 pedestrian fatalities annually in the European Union—representing approximately 27% of all traffic-related deaths—the integration of efficient obstacle detection and warning systems has become an urgent priority.

For tram-specific operations, ADAS must account for the constrained trajectory of rail-based vehicles and their limited manoeuvrability. Consequently, these systems must be capable of:

1. Identifying obstacles along the fixed path of the tram;
2. Estimating the Emergency Braking Distance (EBD) in real time, based on instantaneous speed and track conditions;
3. Providing clear and timely multimodal warnings to the driver;
4. Triggering active braking when the driver does not respond appropriately.

Contemporary ADAS solutions increasingly incorporate Multi-Target Tracking (MTT) algorithms that fuse data from LiDAR, radar, and camera sensors to improve object recognition and tracking accuracy. Although ADAS is not considered a safety-critical subsystem in the same way as Automatic Train Protection, it plays a crucial supporting role in enhancing driver perception. A key challenge lies in avoiding excessive false positives, which may increase under certain environmental conditions and risk undermining trust in the system. ADAS must therefore balance sensitivity and reliability, ensuring that warnings enhance situational awareness rather than compromise driver performance or increase cognitive load.

A particularly relevant reference for this research is the **Horizon SuperDrive** interface, an advanced Human–Machine Interface (HMI) solution designed to support assisted driving in semi-autonomous automotive contexts. Although originally developed for road vehicles, the Horizon case study illustrates how sensor data, environmental perception, and collision-avoidance logic are translated into driver-facing visualizations, multimodal alerts, and decision-support mechanisms. Its architecture offers valuable insights into current design approaches, highlighting both technological potential and critical limitations that inform the redesign strategies explored in this paper.

Within the tram context, the continuous variation of certain operational elements—such as the next stop, dwell time, and upcoming stations—contributes to an inherently unstable interface structure, often lacking fixed visual anchors that would support efficient visual scanning. In professional driving interfaces, operators must be able to distinguish at a glance which components remain constant and which are subject to change. The absence of stable reference points increases cognitive load, requires frequent micro-readings, and reduces the driver's ability to detect critical information immediately. A further issue concerns the lack of a consistent visual language for comparable elements across different screens. Identical functions—such as time indicators, system status signals, or operational distance values—are often rendered using varying graphic weights, typographic hierarchies, or spatial arrangements. This visual heterogeneity disrupts the formation of a stable mental model and forces drivers to repeatedly reinterpret the interface logic when switching between views. In professional systems operating under time pressure, visual consistency is not a superficial aesthetic concern but a fundamental prerequisite for safety and usability.

Finally, the placement and behavior of high-impact operational controls—such as confirmations, alerts, or system resets—are, in some cases, insufficiently differentiated from purely informational elements. This ambiguity may lead either to hesitation or to unintended interactions, particularly in high-stress situations. The lack of a clear distinction between functional layers—information, navigation, and action—emerges as a core issue highlighted by heuristic and comparative analyses of existing systems and represents a key area for intervention during the redesign phase

USER-CENTRED INQUIRY: WORKSHOP-BASED FIELD RESEARCH

To complement the heuristic evaluation, a user-centred inquiry was conducted through a design workshop conceived as a framework for integrated field research. The workshop involved postgraduate design students from the Master's program in Advanced Sustainable Design at the University of Florence and embedded direct observation, questionnaires, and semi-structured interviews with professional tram drivers operating on the Florence tramway network.

This workshop-based field research approach enabled the investigation of interface usability from both a design-oriented perspective and a situated operational viewpoint, allowing analytical insights to be grounded in real-world driving practices and constraints. The workshop was structured into four main phases, each combining analytical activities with empirical research methods.

Observation and Mapping

Students were asked to reverse-engineer the existing interface by reconstructing the navigation logic, mapping screen flows, and identifying potential inconsistencies or redundancies. As part of the embedded field research, students directly observed drivers during service routes in order to understand real operational scenarios, task sequences, and contextual constraints. This phase enabled participants to relate interface structures to the temporal rhythms and pressures of everyday tram operation.

Problem Framing

Through guided discussions, participants identified recurrent issues related to cognitive load, visual hierarchy, task prioritization, and potential error-prone situations that could compromise safety. This phase allowed students to align their analytical findings with the demands of real-time driving operations, shifting the focus from abstract usability issues to operationally critical conditions.

User Inquiry: Questionnaires and Interviews With Tram Drivers

A set of semi-structured questionnaires and interviews was administered to Florence tram drivers as an integral component of the workshop. The investigation focused on key aspects of the user experience, including the readability of status indicators, the ease of locating relevant functions, perceived workload, the frequency of errors or near-errors, and confidence in the interface during both regular and perturbed service conditions. Interviews were conducted both in the depot and *in situ* during non-operational hours, enabling drivers to comment on specific screens while interacting directly with the interface. Across interviews, drivers consistently reported difficulties in rapidly identifying dynamic information—such as regulation status or distance to the preceding vehicle—as well as a general sense of visual overcrowding. Moments of hesitation when navigating between sections under time pressure were also frequently mentioned.

Conceptual Reframing

In the final phase, students developed conceptual and interactive mock-ups aimed at reorganizing the information architecture, reducing visual clutter, and improving safe access to critical functions. These proposals translated drivers' observations and operational insights into concrete design actions for future tram interfaces.

Overall, the workshop-based field research provided valuable insights into how design-trained but non-specialist users reconstruct system logic and where their expectations diverge from existing solutions. The consistent misalignment identified between informational structures and operational priorities reinforced the results of the heuristic analysis and informed the definition of targeted design requirements for semi-autonomous tram systems. The insights emerging from this workshop-based field research constitute the empirical basis for the identification of interface criticalities and the definition of design requirements discussed in the following section.

COMPARATIVE REFERENCE: INDUSTRIAL HMI APPROACHES IN RAIL SYSTEMS

As part of the broader case study, a comparative reference analysis was conducted on industrial Human–Machine Interface (HMI) solutions adopted in contemporary rail-driving systems, including interfaces developed by Hitachi for international contexts. The objective of this analysis was not to evaluate a specific product performance, but to examine how large-scale industrial solutions address shared challenges related to information hierarchy, visual clarity, and operational safety.

From a comparative perspective, the Hitachi interface demonstrates a consolidated visual grammar and a clear grouping of functional elements, reflecting established industrial standards in rail-system HMI design. In particular, the alignment between iconography and functional clusters provides a useful reference for understanding how consistency and recognizability are pursued in complex operational environments.

At the same time, the analysis highlighted a set of recurrent patterns that appear to be characteristic of the sector as a whole rather than attributable to individual design choices. These include the dense coexistence of dynamic information streams, the visual articulation of alarms and system states, and the challenge of maintaining clear prioritization under conditions of high informational load. Such patterns suggest that interface complexity is often a structural consequence of technological and regulatory requirements rather than the result of isolated design shortcomings.

The comparative perspective therefore reinforced the need to articulate explicit and context-sensitive design requirements tailored to tramway systems, where interaction frequency, task coupling, and situational awareness differ significantly from both consumer interfaces and heavy-rail control environments. Rather than positioning industrial solutions as benchmarks to emulate or critique, this analysis served to contextualize the Florence case study within broader international practices and to identify shared design tensions that warrant systematic reconsideration.

FROM CRITICALITIES TO NEW DESIGN REQUIREMENTS

By integrating findings from the heuristic evaluation, the workshop phases and outputs, the drivers' feedback, and the comparative reference analysis, a coherent set of key design requirements emerges. These requirements form the conceptual foundation for the subsequent redesign phase:

1. **Establish a stable and predictable information hierarchy.** Primary operational data (speed, regulation status, distance to the preceding vehicle, next stop) must be visually dominant and remain in fixed positions across screens. Secondary information should be consistently grouped and visually subordinated, for instance through modular widgets.
2. **Reduce cognitive load through structural simplification.** The navigation system should minimize the number of top-level sections and avoid placing infrequent or high-impact actions (e.g., logout) alongside primary navigation items. A reorganized navigation bar and a clearly articulated settings area should ensure safe access without accidental activation.
3. **Implement a consistent visual language.** Typography, iconography, spacing, and alignment must follow a unified system based on a shared grid. Elements performing similar functions should share identical visual attributes and behaviors across all screens.

4. **Redesign color semantics according to international conventions.** Color coding should follow a predictable semantic axis: red for critical or abnormal states, green for regular conditions, and neutral hues for stable information. Colors used for call-to-action elements must not overlap with those representing system status.
5. **Provide visual anchors for dynamic information.** Rapidly changing values should be associated with stable graphical structures—such as bars, timelines, or consistent modules including alerts and notifications—allowing drivers to perceive trends at a glance rather than relying exclusively on numeric changes.
6. **Ensure safe and context-aware action placement.** High-impact commands must be spatially separated from routine navigation, clearly labelled, and accompanied by confirmation mechanisms to prevent unintended activations.
7. **Respect safe areas and touch-interaction constraints.** Margins, hit areas, and spacing must comply with ergonomic guidelines for touch interfaces used in constrained and vibration-prone environments, ensuring accessibility even during unexpected vehicle movements.

CONCLUSION

This paper has framed UX/UI design as a critical infrastructural component in contemporary and future tram systems, particularly within the transitional phase toward semi-autonomous and autonomous operation. By analyzing tram mobility as a human–intelligent sociotechnical system, the research demonstrates that safety, efficiency, and trust are not inherent properties of automation, but emergent qualities shaped through interaction design.

Through a combined methodological approach—integrating state-of-the-art analysis, heuristic evaluation, comparative interface review, and user-centred field research involving both design practitioners and professional tram drivers—the study identified key interaction breakdowns that directly affect situational awareness, cognitive workload, and decision-making in safety-critical contexts. These findings were translated into a structured set of design requirements, providing actionable guidance for the redesign of tram driver interfaces

The results highlight the role of intelligent interfaces as active mediators between human cognition and automated system behavior. In semi-autonomous tram environments, interfaces shape how drivers perceive system states, interpret automation intent, and calibrate trust. Design decisions related to information hierarchy, visual consistency, multimodal feedback, and action placement therefore acquire ethical and operational relevance, influencing both performance and acceptance.

The study further positions the current hybrid phase of tram automation as a cultural and communicative transition, in which drivers progressively shift from direct control toward supervisory roles. In this scenario, UX/UI design supports not only operational safety but also learning, adaptation, and the redefinition of professional practices. Emerging technologies increasingly adopted in this context—such as augmented, virtual, and mixed reality—further expand this role, enabling enhanced situational awareness, simulation-based training, and gradual exposure to higher levels of autonomy.

Overall, this research demonstrates how design-driven, human-centred methodologies can generate transferable knowledge for intelligent transport systems. By articulating concrete interaction principles and design requirements grounded in real-world operation, the paper underscores the strategic role of UX/UI design in ensuring that autonomous mobility systems remain transparent, trustworthy, meaningful, and intuitive, aligned with human capabilities throughout the transition toward fully automated public transport. As tram networks continue to expand—such as in the case of Florence—these design requirements become increasingly fundamental, reinforcing the need to manage and simplify interface complexity in safety-critical mobility systems.

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