Head-Up Displays for ETCS

by

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Introduction

Sweden's railway system is a critical component of national transport, carrying large volumes of passengers and freight daily. To maintain efficiency and safety, Sweden is transitioning from the ageing Automatic Train Control (ATC) system to the European Rail Traffic Management System (ERTMS), with ETCS as its signalling subsystem. While ETCS enables increased capacity and cross border interoperability, it also alters the train driver's work environment by moving essential information from trackside signals to an in-cab driver–machine interface (DMI). Recent simulator studies indicate that ETCS may reduce drivers' outward visual attention, leading to increased in-cab glances, particularly at stations and level crossings (Olsson et al., 2025). This is concerning given that most railway accident fatalities involve unauthorised persons on the track or level crossings (Eurostat, 2025). Reduced outward attention may therefore compromise hazard detection in high-risk areas. One potential approach to mitigate this effect is the use of Head Up Displays (HUDs), which present critical information within the operator's forward field of view. HUDs have been shown in other transport domains to support attention allocation by allowing simultaneous access to external and system information (Ward & Parkes, 1994; Newman, 1995). However, no prior studies have designed and empirically evaluated an ETCS Level 2 HUD using eye tracking. This study investigates whether integrating a HUD with ETCS can improve train drivers' visual attention in safety critical environments. A HUD may reduce attentional switching between external signals and in-cab displays, thereby supporting visual attention allocation.

Aim and Research Questions

The aim of this study is to design and evaluate an ETCS Level 2 Head-Up Display for train drivers and to examine its effects on visual attention from a safety perspective using a driving simulator and eye-tracking. For this, the following research questions (RQ) were formulated: *RQ1: How does an ETCS-HUD affect train drivers' visual attention?; RQ2: What information*

should an ETCS-HUD present to support safe driving?; RQ3: How should ETCS-HUD visualisation and placement differ from the standard ETCS?

Method

The study followed a two-phase design. First, an exploratory design study was conducted to develop an ETCS Head Up Display (HUD). Second, the final HUD prototype was evaluated in a simulator pilot study using eye tracking. Visual attention results were compared with previously collected ETCS non-HUD data from Olsson et al. (2025), forming a between subjects' experimental comparison.

Participants

Participants were recruited through convenience sampling and were required to be current, former, or trainee train drivers with knowledge of ETCS Level 2. Participation was voluntary and compensated with ice cream vouchers.

Phase 1: HUD Design

Three experienced train drivers with a mean age of 41.6 years and train driving experience of 17.6 years participated in semi-structured interviews and a design workshop. All had experience with ETCS Level 2, including one with simulator-only exposure. Sessions were conducted online via Microsoft Teams. A Research through Design approach was used, with iterative prototyping in Figma informed by literature, usability heuristics, and expert feedback. Interviews focused on HUD content, information density, visualisation, colour usage, and placement. Based on interview findings, multiple design proposals were refined and discussed in a group workshop, where participants collaboratively selected and modified a preferred design.

Phase 2: Simulator Pilot

The simulator pilot was conducted in Nässjö, Sweden, using a transportable Regina locomotive simulator provided by VTI, identical to that used by Olsson et al. (2025). A total of 6 train drivers participated, and the mean age was 44 years. All participants had knowledge of ETCS Level 2, and 5 had prior operational experience. One participant was excluded due to data loss. The final HUD prototype was rendered directly on the simulator display, with transparency and colour choices used to approximate optical HUD characteristics. Eye movements were recorded using head-mounted eye-tracking glasses from Pupil Labs, capturing scene video and gaze coordinates. Visual attention was assessed by analysing the distribution of in-cab versus outward glances, with particular focus on safety-critical scenarios such as stations and level crossings.

Data Analysis

Interview transcripts were analysed using manifest content analysis (Bengtsson, 2016) focused on HUD placement, essential information content, and perceived effects on attention. Based on the interview results, the prototype was refined and subsequently reviewed in a design workshop. Remaining design issues were addressed collaboratively, resulting in a final HUD design used for simulator testing. Eye-tracking data from the simulator pilot were analysed using predefined areas of interest (AOI) covering the HUD, the conventional DMI, and the external forward view. The analysis focused on the distribution of in-cab versus outward glances, particularly in safety-critical situations, to assess whether the HUD improved visual attention.

Results

The final ETCS head-up display (HUD) design for five driving scenarios is presented in Figure 1a-e. Across all scenarios, the HUD was positioned centrally at the bottom of the windshield, with size adjusted to viewing distance. The design includes core ETCS DMI information while adapting layout, colour coding, and information prioritisation to support direct forward viewing.

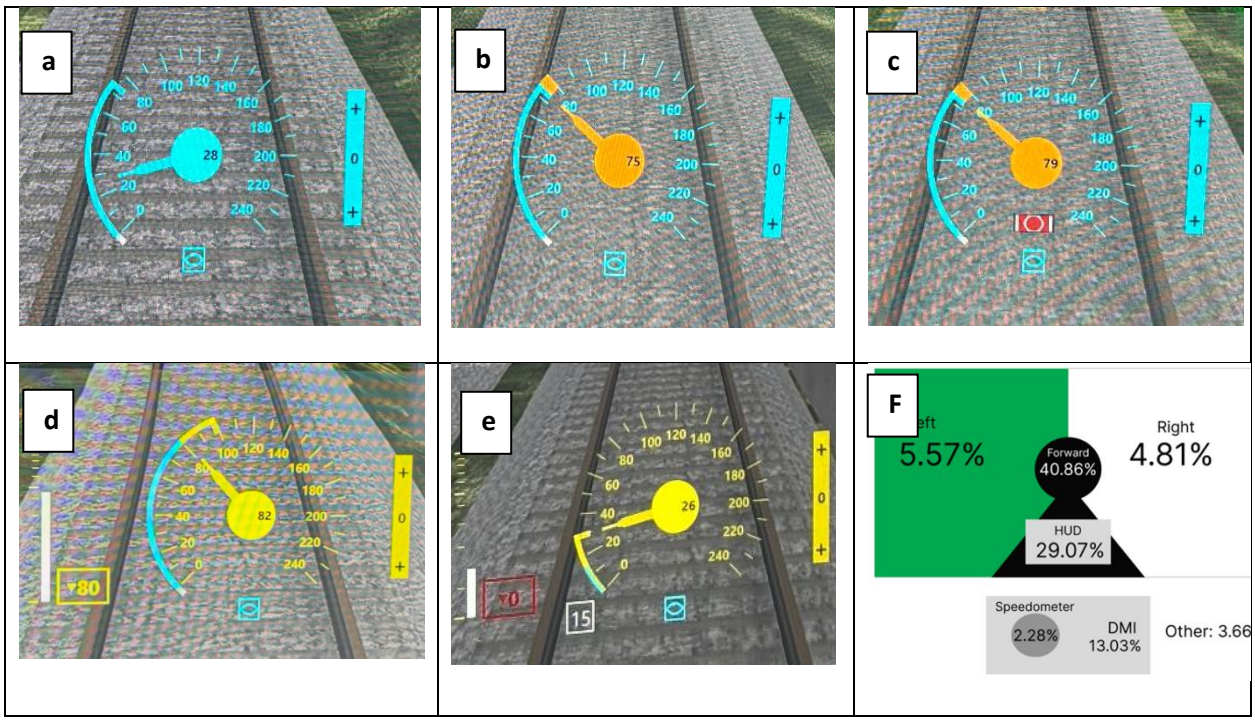

Figure 1: Normal operation (a); Exceeding speed limit (b); Substantially exceeding speed limit – safety brakes (c); approaching a speed decrease (d); Approaching a full stop and release speed (e); Percentages at each AOI with HUD defined as its own AOI (f).

Participants appreciated the clear presentation of speed and current gradient, the placement of elements, and the colour-coded mode changes. Most reported reduced need to consult the in-cab DMI when adjusting speed ahead of restrictions. Preferences for additional information varied, but all except one had a strong willingness to use an ETCS HUD in real-world operations.

Eye-tracking analyses examined glance distribution across AOIs. When the HUD was treated as a separate AOI, no significant difference in total forward glance percentage was found between ETCS and ETCS-HUD conditions (Figure 1f). However, when HUD glances were included in forward glances, the ETCS-HUD condition showed a significantly higher proportion of forward glances compared to ETCS without a HUD ($p < .001$, large effect).

No significant difference was observed in glances toward the DMI excluding the speedometer. In contrast, speedometer glances were significantly reduced in the ETCS-HUD condition compared to ETCS alone ($p < .001$), indicating that speed monitoring was effectively transferred to the HUD. Due to the small sample size, the findings should be interpreted with caution.

Discussion and Conclusions

This pilot study explored whether an ETCS-HUD could support attention to the forward view while providing essential system information. Eye-tracking results showed that when HUD glances were considered part of forward viewing, the ETCS-HUD condition produced a significantly higher share of forward-directed attention compared to ETCS alone. When the HUD was treated as a separate area of interest, no significant reduction in forward attention was observed, suggesting that the HUD redistributed attention away from less relevant areas rather than diverting it from the track ahead. Although HUDs may risk cognitive capture (Gish & Staplin, 1995), the forward view still received a larger proportion of visual attention than the HUD, indicating limited attentional cost.

Survey responses further supported these findings. Participants generally appreciated the HUD design and reported reduced reliance on the in-cab DMI, particularly for speed monitoring, which was reflected in fewer speedometer glances toward the DMI. At the same time, several participants expressed a desire for richer planning information, especially regarding gradients, highlighting a balance between simplicity and informational completeness.

Most participants preferred the tested HUD placement slightly below the natural forward line of sight, consistent with automotive HUD research (Topliss et al., 2019). Overall, the results

suggest that the proposed ETCS-HUD can reduce DMI dependence and support forward-oriented attention. However, altered gaze behaviour cannot be equated with improved safety. As a pilot study with a small sample, further research is needed to assess effects on driving performance, safety, and long-term use under operational conditions. Given the small sample and exploratory design, the findings should be interpreted with caution.

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