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Enhancing User Adoption of Electric Trucks through Fluid HMI Design for Range Anxiety Mitigation

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Executive Summary

Zero-emission heavy-duty vehicles have the potential to revolutionize commercial transport, yet their adoption is hindered by significant challenges, primarily range anxiety—drivers' fear of running out of energy before reaching a refueling station. This study introduces a novel Human-Machine Interface design that effectively addresses range anxiety through fluid, user-centered features. These "fluid HMIs" integrate real-time monitoring of hydrogen fuel levels, dynamic range estimation, and intelligent refueling station navigation. By providing predictive alerts, optimizing route planning, and adjusting to road conditions and environmental factors, the fluid HMI ensures seamless energy management. This adaptive system enhances driver confidence, reduces cognitive load, and promotes operational efficiency, thereby fostering greater trust in zero-emission heavy-duty vehicles and supporting their wider adoption by fleet operators.

Keywords: Fuel Cell Electric Vehicles, Heavy Duty Electric Vehicles & Buses, Infotainment Systems and Trends, Energy Management, Human-Machine/Computer Interaction.

1 Introduction

Human-Machine Interfaces (HMIs) in vehicles have evolved dramatically in recent decades, transitioning from basic, mechanical interfaces to sophisticated digital systems. In internal combustion engine (ICE) vehicles, traditional HMIs typically focused on displaying only essential metrics. However, the increasing adoption of zero-emission heavy-duty vehicles (z-HDVs) introduces new complexities, particularly in the areas of energy management and refuelling and charging infrastructure. z-HDVs drivers require real-time, context-aware data on energy storage unite health, range, energy consumption, and refuelling options. This shift necessitates the development of more fluid interfaces capable of handling these complexities, which static HMIs are ill-equipped to address [1].

In conventional ICE trucks, HMIs focus on providing standard metrics, such as speed, fuel levels, and engine temperature. These systems lack the complexity needed to manage the range, refuelling infrastructure, and battery/fuel cell health concerns of z-HDVs vehicles. With the transition to z-HDVs, traditional static HMI systems are insufficient to address the demands of range management and real-time energy consumption. Fluid HMIs, by contrast, dynamically adjust to various variables such as driving conditions, terrain, and on-board energy status, offering personalized route planning and energy management suggestions. These adaptive interfaces are essential for overcoming range anxiety, which is a key concern for drivers transitioning from ICE to z-HDVs [2][3].

Range anxiety refers to the fear of a depleted on-board energy before reaching a refuelling/charging station, and it represents one of the most significant barriers to the adoption of z-HDVs, especially in the long-haul commercial trucking sector [4][5]. Drivers of z-HDVs face heightened concerns due to the unpredictable energy consumption caused by factors such as cargo weight, driving terrain, and weather conditions. To address these concerns, it is crucial to design HMIs that provide real-time information, predictive energy management, and refuelling station availability. Responsive HMI designs can dynamically adapt to evolving driving conditions, reducing the range's uncertainty and empowering drivers with reliable information to plan their journeys.

An interface that is adaptive, dynamic, and user-centric is known as a fluid HMI (*f*-HMI). It continuously adjusts to real-time data on vehicle performance, user preferences, and environmental factors. For z-HDVs, *f*-HMIs are designed to offer feedback, such as energy conservation tips, as well as seamless access to nearby refuelling/charging infrastructure. These features not only reduce the range concern of drivers but also improve decision-making in situations, such as managing on-board energy levels during long hauls or navigating to the nearest refuelling station when energy is running low.

User-Centered Design (UCD) is an approach to interface design that prioritizes the user’s needs, behaviors, and preferences throughout the development process. UCD principles are especially relevant to z-HDVs truck HMIs, where drivers require intuitive, easy-to-navigate interfaces that minimize distractions and stress. In the context of range anxiety, UCD principles help ensure that drivers receive the most pertinent information, such as real-time energy levels and refuelling station availability, without overwhelming them with unnecessary data. Personalized HMI systems designed with UCD principles can adapt to individual driving patterns, providing more accurate predictions for energy consumption and refuelling needs [6][7].

Artificial intelligence (AI) plays a pivotal role in *f*-HMI design by enabling the system to adapt to real-time conditions and anticipate the driver's needs. Machine learning algorithms can analyze a variety of inputs, including energy level status, driving suggestions, mode of operations (e.g. eco-mode), route data, and environmental factors, to predict the best course of action. For example, AI can recommend energy-saving driving modes or suggest the most efficient refuelling stops based on real-time traffic and energy usage patterns. These AI-driven systems significantly reduce the range concerns of drivers, as they either ensure decisions are based on accurate and relevant data or timely suggestions for refueling stations or stops based on the vehicle's current range and route [2],[3],[5].

Despite advancements in z-HDVs vehicle HMI design, existing research has largely focused on passenger EVs, leaving significant gaps when it comes to truck-specific HMI needs. Current literature adequately addresses the challenges faced by long-haul electric truck drivers, such as managing range under varying cargo loads and navigating to refueling stations across vast distances. However, the role of HMI in reducing range anxiety is inadequately addressed, with limited focus on how effective HMI design can alleviate these concerns. This paper seeks to address these gaps by focusing on *f*-HMI systems tailored to z-HDVs, with a particular emphasis on mitigating range anxiety through real-time adaptive features via HMI [2],[3],[5].

The primary goal of this paper is to address the gap in research by exploring how *f*-HMIs can alleviate range anxiety and improve the user experience for electric truck drivers. The research aims to answer the following question: *“How can f-HMIs help mitigate range anxiety and enhance UX in z-HDVs?”.*

This paper is organized as follows: section 2 will go through the methods used to produce a *f*-HMI specific for z-HDV, and the results of implementing those methods are shown in section 3, a discussion with the implications for future HMI design in electric trucks are in section 4, and finally section 5 gives the conclusion of the paper.

2 Methodology

The development of the *f*-HMI for z-HDVs is grounded in user-centred design (UCD) principles. UCD emphasizes continuous engagement with end users—electric truck drivers, in this case—to gather insights into their specific needs and challenges. The design process is iterative, meaning that it involves repeated cycles of design, feedback, and refinement. This allows for the continuous incorporation of real-world user feedback to improve the interface over time.

The fluidity characteristics for the proposed HMI are crucial for ensuring that zero-emission heavy-duty trucks (both battery-electric and fuel cell) effectively reduce range anxiety while meeting fleet operators' logistical needs, such as timely delivery of goods. The proposed HMI will facilitate efficient communication between the driver, vehicle, and both infrastructure and environment, providing timely, accurate feedback that supports the driver in achieving delivery goals. The following properties characterize the fluid interface:

1. Promoting Flow: The HMI will promote flow by providing timely, actionable feedback for range management. i) It will offer real-time information on the vehicle's range, estimated delivery times, and proximity to charging or refueling stations, helping the driver manage range anxiety by informing them of potential stops well in advance. ii) Additionally, the system will minimize distractions by using purposeful audio-visual cues to alert the driver of critical conditions, such as low hydrogen levels, low battery, road congestion, or upcoming rest requirements, allowing the driver to stay focused on the road and driving tasks.

2. Supporting Direct Guidance:The HMI will support direct guidance for the driver through several key features. i) It will provide clear, simple instructions for managing the vehicle’s range, such as guidance on adjusting driving behavior (e.g., speed or regenerative braking) to maximize range while meeting delivery time constraints. ii) The system will offer continuous infrastructure awareness by displaying critical information, such as charging or refueling stations along the route, traffic conditions, and potential delays, enabling the driver to plan their route efficiently and ensure timely deliveries. iii) By presenting relevant, easy-to-understand information on a single interface, the HMI will minimize cognitive load for decision-making, allowing the driver to quickly decide when and where to stop for charging or refueling without unnecessary stress. iv) Finally, the HMI will streamline critical actions, such as initiating a refuelling/charging stop or adjusting route plans, into a one-step process, reducing the complexity of decisions while on the road.By focusing on these fluid interface properties, the HMI for both battery-electric and fuel cell zero-emission heavy-duty trucks will support drivers in managing range anxiety while ensuring timely deliveries. This approach not only reduces the cognitive burden on the driver but also aligns with the operational needs of fleet managers, ensuring that goods are delivered efficiently while maintaining safe and compliant driving practices.

This study employed an iterative UCD process to develop and refine *f*-HMI systems for z-HDVs [6][7]. The main elements of this process included: i) User Research: The initial step involved collecting requirements from truck drivers through interviews and observational studies, focusing on their concerns regarding range anxiety, energy management, and real-time refuelling information. The insights gathered from these interactions informed the first design iteration of the HMI. ii) Prototype Development: Using the insights gained from user research to develop HMI prototypes, focusing on adaptive range alerts, refuelling station navigation, and energy management. iii) User Testing: Prototypes are to be tested in both simulated and real-world environments. Simulations covered a range of driving scenarios, such as urban routes, highways, and low-H2fuel/charge situations, to assess how well the *f*-HMI mitigated range anxiety. iv) System Refinement:

Based on user feedback, the HMI is refined to reduce cognitive load, improve ease of use, and optimize personalized alerts and energy-saving tips.

A flowchart illustrating the iterative design process is shown in Fig 1. The design process is cyclical, where each iteration builds upon the insights gained from previous phases. At the heart of this process is continuous user feedback, which is gathered from drivers using the system in real-world conditions. This feedback informs adjustments and refinements to the design, ensuring that each subsequent prototype better addresses the drivers' evolving needs and preferences. The iterative nature of the process allows for the development of a testable prototype at each stage, which can be evaluated and improved based on actual user experiences. By engaging in this constant cycle of testing, feedback, and refinement, the *f*-HMI system is able to evolve dynamically, adapting to real-world challenges and ensuring that it aligns with the drivers' expectations and operational requirements. Ultimately, this iterative approach leads to a more user-centered and effective f-HMI system that evolves in direct response to the needs and preferences of the drivers

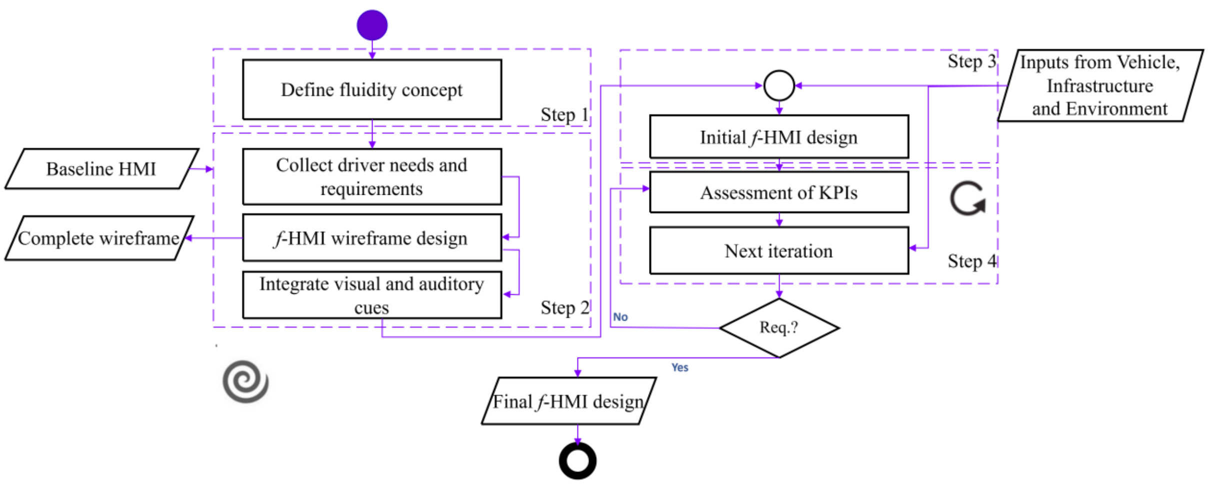

Figure 1. Flowchart of Iterative Design Process

To evaluate this process, metrics that well reflect the improvement in performance and range anxiety must be identified. The effectiveness of the *f*-HMI should be evaluated using UX metrics. Those metrics are used as key performance indicators (KPIs) that are considered in determining if the HMI is preforming according to the drivers and system requirements. The KPIs are: i) Ease of Use: Evaluates how intuitive the interface is in providing battery information and suggesting refuelling options. ii) Task Efficiency: Measures how quickly drivers can find critical information related to range and refuelling stations. iii) Cognitive Load: Assesses whether the HMI reduces the mental effort required to manage energy and refuelling/charging stops. iv) User Satisfaction: Surveys drivers on their confidence in managing range anxiety and their overall satisfaction with the system. Those metrics are measured in simulation and then in real-world testing, as explained in the following section.

Prototypes are initially tested in a simulated environment that mimicked real-world driving conditions, including highway driving, urban environments, and various energy depletion scenarios. Then, the prototypes should be deployed in future work for real-world testing in z-HDVs, allowing drivers to interact with the system under actual driving conditions. Key areas of focus included range alerts, route optimization for refuelling stops, and personalized energy management tips.

3 Results

This research demonstrates that *f*-HMIs significantly mitigate range anxiety for fuel cell trucks by providing real-time updates on hydrogen fuel levels, energy consumption, and refueling station availability. Based on user feedback, several critical features were incorporated into the *f*-HMI:i) Real-Time Hydrogen Fuel Level and Range Alerts: The interface prominently displays the current hydrogen fuel level, along with a clear estimation of the remaining range based on real-time driving habits and road conditions. Drivers appreciate constant awareness of how far they can travel before needing to refuel.ii) Refueling Station Availability and Integration: The *f*-HMI integrates with navigation systems to display nearby refueling stations, highlighting those that are within the truck's current range based on current hydrogen levels and real-time traffic data. This feature is critical in reducing range anxiety and ensuring drivers can confidently plan their routes.iii) Predictive Alerts: Drivers are notified in advance if their current route may result in low hydrogen levels before reaching a refueling station. Based on energy consumption, traffic conditions, and driving habits, the f-HMI provides alternative routes optimized for energy conservation. The system suggests these routes or refueling stops well before the hydrogen tank reaches critical levels.iv) Visual and Auditory Cues: Visual indicators of hydrogen fuel levels are complemented by auditory alerts, ensuring that the driver receives important information without being distracted from driving. Visual cues provide clear, easy-to-read hydrogen fuel icons and range indicators, while auditory cues deliver more urgent notifications, such as when fuel levels drop below a critical threshold. The *f*-HMI's ability to adjust based on driving conditions (e.g., switching to energy-saving mode in traffic) contributes to a more seamless and intuitive driving experience.

Fig. 2 illustrates the primary display of the f-HMI, which visualizes critical operational parameters through distinct icons. These include the hydrogen fuel cell tank temperature, the current hydrogen fuel level, and the small auxiliary battery that supports the fuel cell system. The interface also integrates a map that displays the nearest hydrogen refueling stations, allowing for real-time proximity analysis. Additionally, the route is depicted along with an estimated range, providing the driver with essential data to make informed, efficient decisions regarding refueling stops and energy management throughout the journey.

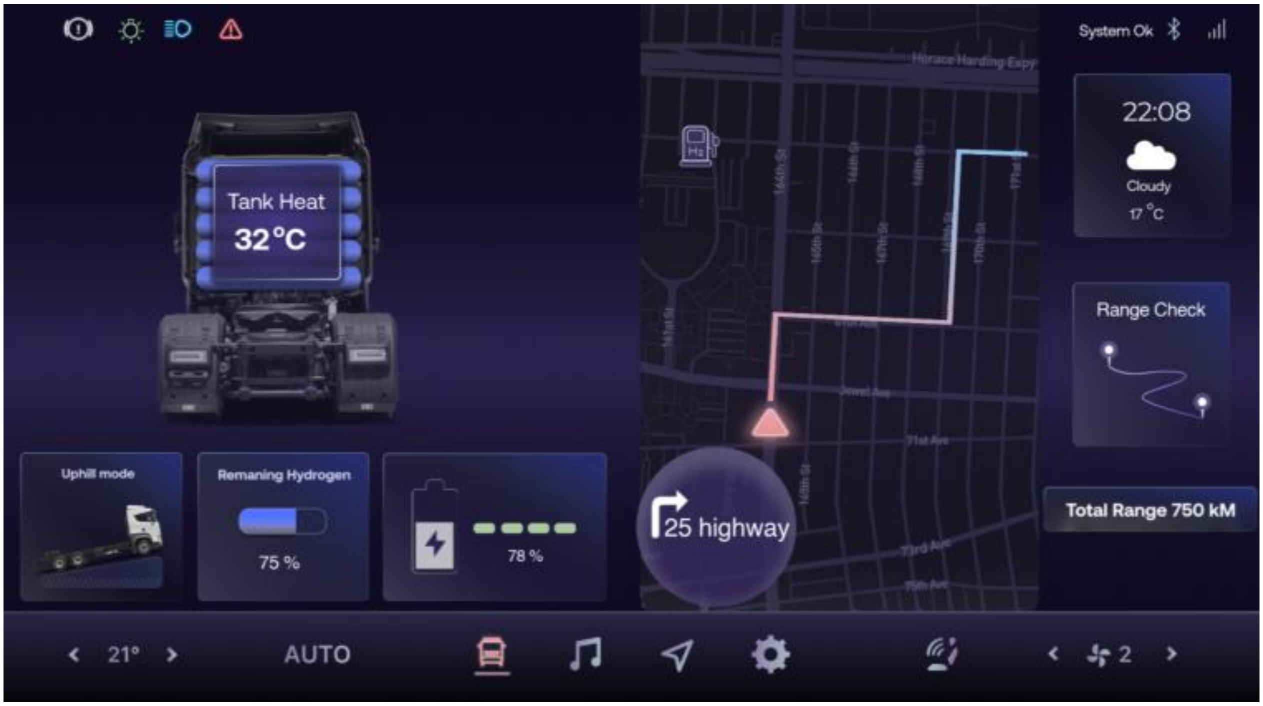

Figure 2. *f*-HMI main interface showing hydrogen fuel levels, auxiliary battery status, nearest H2 refueling station, and route with range estimation.

The iterative design process facilitated ongoing refinement of the interface through continuous real-world user feedback. By incorporating driver input at each stage of development, the final f-HMI was precisely aligned with user requirements, resulting in high levels of satisfaction with the system. Objective performance metrics, including reduced reaction times to alerts, provided quantitative evidence that the f-HMI improved both usability and overall system efficiency.

4 Discussion

The iterative design process implemented in the development of the fluid Human-Machine Interface (*f*-HMI) has proven to be an effective approach in addressing the operational challenges faced by drivers of zero-emission heavy-duty trucks. Through the continuous integration of user feedback, the interface has been progressively refined to meet the specific demands of real-world driving conditions. This iterative development process has ensured that the final system is well-suited to enhance operational efficiency, alleviate range anxiety, and optimize vehicle energy management. The *f*-HMI incorporates several key features aimed at improving the driver's ability to manage vehicle range effectively. Real-time monitoring of hydrogen fuel levels, auxiliary battery status, and proximity to refueling stations are fundamental components of the system, providing the driver with critical information necessary to make informed decisions about refueling. The integration of route planning and range estimation further augments the system's utility, enabling drivers to anticipate refueling needs based on remaining fuel and driving conditions. Additionally, the predictive alert system, which informs the driver when refueling may be required before reaching a station, proactively mitigates potential operational disruptions, thus reducing the stress associated with range anxiety.

Preliminary assessments of the system's usability indicate that the *f*-HMI significantly enhances the driver's situational awareness by delivering relevant data in an intuitive and easily interpretable format. The interface's design minimizes cognitive load, presenting key information—such as H2 fuel levels, battery status, and refueling station proximity—in a manner that does not overwhelm the driver. This allows the driver to focus on critical driving tasks while maintaining awareness of operational constraints, thus supporting safe and efficient vehicle operation. Although the study is ongoing, initial findings suggest that the *f*-HMI has the potential to improve both individual user experience and fleet-level operational performance. The integration of real-time data on hydrogen fuel levels, refueling station availability, and route optimization contributes to more efficient energy management, which can support fleet managers in achieving operational goals such as timely deliveries and optimal fuel usage. Furthermore, by continuously refining the system based on user feedback, the *f*-HMI is expected to enhance driver satisfaction and facilitate wider adoption of zero-emission heavy-duty trucks. In conclusion, the development of the *f*-HMI highlights the critical role of a user-centered, iterative design approach in advancing the usability of interfaces for emerging vehicle technologies. While the study is still in progress, the current findings underscore the potential of the *f*-HMI to enhance driver performance, optimize fleet operations, and contribute to the broader goal of sustainable and efficient zero-emission transportation.

5 Conclusion

This study demonstrates that fluid Human-Machine Interfaces (*f*-HMIs) hold significant potential in addressing the challenge of range anxiety in zero-emission heavy-duty vehicles (z-HDVs). By integrating real-time data, adaptive interface design, and seamless connectivity with refueling infrastructure, *f*-HMIs offer an intuitive, user-centered experience that can help drivers manage fuel levels and plan refueling stops more effectively. Early findings suggest that drivers feel more confident and less concerned about fuel depletion when using a system that provides clear, actionable information tailored to driving conditions. As the transportation sector transitions towards sustainable solutions, z-HDVs are likely to become more prevalent. *f*-HMI systems that adapt to diverse driving environments, provide real-time operational feedback, and integrate smoothly with refueling infrastructure will be essential in overcoming barriers to EV adoption, particularly range anxiety. With ongoing research and development, these systems have the potential to improve the user experience, enhance operational efficiency, and contribute to greater sustainability in commercial transportation.

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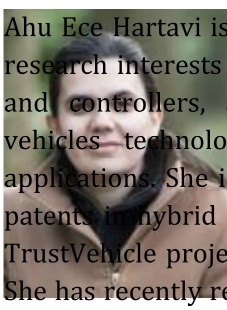
Presenter Biography



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