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A User-Centred Design Approach for Inclusive and Trustworthy Human-Machine Interfaces in AI-Based CCAM Systems

Turkan Hentati[1] and Katerina Touliou[2]

[1]Applus IDIADA, Spain
[2]Centre for Research and Technology Hellas (CERTH), Hellenic Institute of Transport (HIT), Thessaloniki, Greece

ABSTRACT

Human-Machine Interfaces (HMIs) for AI-based Connected, Cooperative and Automated Mobility (CCAM) systems are too often designed around an implicit "average user", typically a young, experienced, able-bodied driver, despite growing evidence that user needs vary sharply across age, driving experience, cognitive profile and sensory ability. This paper presents the User-Centred Design (UCD) methodology developed in the AIGGREGATE project to derive inclusive HMI requirements for three automated-driving use cases: collective perception in shared urban spaces (UC-Aa), collective decision-making at SAE Level 4 (UC-Ab), and cooperative highway Take-Over Request (TOR) management (UC-B). Grounded in ISO 9241-210:2019 and the Task–Tool–User triangle, the methodology combined a state-of-the-art review with twenty semi-structured interviews following a mock-up exposure session, involving participants with Mild Cognitive Impairment, ADHD, visual and hearing impairments, older adults, and novice and experienced drivers across six countries. Thematic analysis of the interviews, cross-referenced with pre- and post-exposure questionnaire data, produced 43 interview-derived HMI requirements distributed across user profiles and use cases. Results show that acceptance was conditional rather than binary: participants did not reject the automated-driving concepts, but identified specific, implementable design deficiencies tied to their individual profiles. The paper discusses these profile-specific findings, the resulting interview-derived recommendations, and the sample-size limitations that will guide the next, implementation-focused phase of the project.

Keywords: User-centred design, Human-machine interface (HMI), Automated vehicles, Inclusive design, CCAM, Situation awareness, Take-over request

INTRODUCTION

The rapid integration of AI into CCAM systems is enabling increasingly advanced capabilities, ranging from collective perception to predictive decision-making and automated vehicle control. The success of these systems, however, depends not only on their technical performance but also on whether the humans who share the road with them can understand, trust, and appropriately respond to their behaviour. In safety-critical mobility

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applications, a poorly designed HMI can lead to misuse, disuse, or excessive reliance on automation, with direct consequences for safety.

A persistent challenge in HMI development for automated driving is that requirements are often derived from an assumed "average user". This assumption does not adequately capture the diversity of users who interact with automated mobility systems. Age, driving experience, cognitive profile (e.g., MCI or ADHD), and sensory abilities can influence what users need from an HMI, when they need it, and through which modality information should be delivered. Designing for a single, idealised user may therefore fail to address the needs of populations such as older adults, novice drivers, and persons with disabilities, while not necessarily ensuring optimal usability for the broader driving population.

UCD offers a structured approach to addressing this challenge by integrating users throughout the design process and iterating design concepts based on their needs, capabilities, limitations, and observed interactions. However, its value depends on the rigour with which it is applied. Early studies showed that involving users only informally or late in the development cycle is insufficient to produce reliable design requirements, whereas a structured process of observing users, analysing their behaviour, and iterating designs based on evidence can transform user input into actionable requirements (Gould and Lewis, 1985). Broader surveys of UCD practice similarly indicate that benefits such as improved usability, greater acceptance, and reduced late-stage redesign depend on the systematic application of the methodology rather than merely on the intention to involve users (Vredenburg et al., 2002). Usability engineering likewise emphasises the importance of systematic and repeatable procedures for translating user-study findings into reliable design guidance (Nielsen, 1993). ISO 9241-210:2019 formalises these principles and provides a framework for human-centred design. Against this background, the aim of this paper is to report the UCD methodology and findings developed within the AIGGREGATE project (Hentati et al., 2026), in press). This Horizon Europe project is building trustworthy and resilient AI to make automated driving safer through collective decision-making. The approach combines a review of the state of the art on user needs with user studies conducted across three automated-driving use cases to derive profile-specific HMI requirements for AI-based CCAM systems.

STATE OF THE ART ON USER NEEDS: DIFFERENT PROFILES

Understanding user needs in automated driving first requires understanding how users build awareness of a dynamic driving situation. Endsley's (1995) model of Situation Awareness (SA)—perception, comprehension and projection of environmental elements—provides the theoretical basis: an HMI cannot simply present information; it must support perception of relevant elements, comprehension of their meaning, and projection of their near-future evolution. Deficiencies at any of these three levels degrade decision-making and, ultimately, user acceptance. Recent literature converges on the conclusion that these SA-related needs differ substantially by user profile.

Drivers. Three needs dominate the literature. First, mode awareness: drivers frequently misunderstand which automation mode is active and who is responsible for the driving task, a confusion that combined subjective and behavioural measures can detect and that interface standardisation can reduce (Kurpiers et al., 2020; Eom and Lee, 2022). Older drivers are particularly at risk, since gaze-behaviour changes can signal mode confusion in real time (Haghzare et al., 2022). Second, support during take-over transitions: multimodal HMIs balance faster hazard detection against subjective workload (Shi et al., 2024), and haptic seat feedback has shown positive acceptance for communicating urgency and direction during level transitions (Peters et al., 2025). Third, trust, transparency and perceived control: Nordhoff et al. (2023) propose a "Pyramid of User Needs" placing safety, trust and comfort as foundational, and stress that transparency and perceived control should be prioritised in AV interface design.

Pedestrians and vulnerable road users (VRUs). The absence of a visible human driver removes the informal social cues (eye contact, gestures) that traditionally regulate street interactions. Ground path-projection and external HMI concepts have been shown to reduce pedestrian hesitation and improve perceived safety and trust (Yue et al., 2025; Yu et al., 2025), while multi-pedestrian studies confirm that communication effectiveness depends on ecosystem-level combinations of vehicle-, infrastructure- and personal-device-based signals rather than any single channel (Tran et al., 2024). Rezwana and Lownes (2024) further call for standardised KPIs and testing across diverse pedestrian cohorts.

People with disabilities (PwDs). Accessibility must be designed in from the outset rather than retrofitted. A systematic review of 57 international studies concludes that accessible automated vehicles require multimodal, redundant communication (visual, auditory, tactile), simplified interfaces for cognitive and developmental disabilities, and interface personalisation, with safety prioritised over preference in critical situations (Golbabaei et al., 2024). Beyond the interface itself, accessible automation should support autonomy and social inclusion across the entire travel chain (planning, boarding, travelling, alighting), not merely technical accessibility (Gomez et al., 2024; PAVE Europe, 2025). Across these three profiles, five converging recommendations emerge from the literature: (1) multimodality with cognitive moderation, so redundant channels do not create overload; (2) transparency and explicit communication of system status, intent and limits; (3) standardisation of signals and KPIs, particularly for mode displays and external communication; (4) user-centred and co-design methods, involving end users from the earliest design stages; and (5) inclusive-by-design principles embedded throughout development rather than added at validation. These five principles directly informed the UCD methodology described below.

METHODOLOGY

The User-Centred Design approach. The UCD approach adopted in AIGGREGATE follows ISO 9241-210:2019, applying an early and continuous focus on users, iterative design cycles, multidisciplinary

collaboration and systematic evaluation against user requirements, rather than treating usability as a final validation step. The methodology follows a top-down logic, starting from Hybrid Intelligence and Human-Like Control concepts defined earlier in the project and progressively refining them into use cases, user needs and requirements through iterative engagement with users.

*Hybrid Intelligence (HI) is the structured integration of human expertise and feedback into the AI-based driving system (human in the loop, in the decision loop, or over the loop), supporting all three levels of the system's Situation Awareness: perception (fusing human input with sensor/V2X data), comprehension (human-assisted decision support) and projection (human-informed prediction).

*Human-Like Control (HLC), by contrast, makes the vehicle's own driving behaviour smooth, anticipatory and socially conventional, so that it is more easily read by surrounding road users, indirectly supporting their situation awareness rather than the vehicle's own. AIGGREGATE treats HI and HLC as jointly necessary (rather than HI alone) to achieve both technical performance and user trust, and it is this combined foundation that the process below refines into use cases, user needs and HMI requirements. Following the Task–Tool–User triangle (Bennett, 1984; Eason, 1984; Shackel, 1991; Boy, 2017), the process explicitly considers the interdependencies between the task or scenario context, the tool (the automated system and its HMI), and the user, including needs, capabilities, limitations and diversity of profiles. Correctly calibrated trust is treated as a central design objective throughout: undertrust may lead users to avoid useful automation, while overtrust can produce inappropriate reliance and reduced vigilance (Carsten and Martens, 2019). HMI concepts are consequently designed to support observability (what the system perceives) and predictability (what the system will do next), reducing automation surprise. Critically, the process was explicitly designed to avoid assuming an "average user. AIGGREGATE instead deliberately recruited across age, gender, driving experience and ability, with clear language, accessible consent procedures, unhurried mock-up exposure and multimodal presentation of critical HMI elements built into the interview protocol itself.

Participants. As part of the AIGGREGATE user studies, twenty semi-structured interviews were conducted with participants from six countries (France, Tunisia, Spain, the United Kingdom, Greece and Italy), including experienced drivers, older drivers, drivers with MCI, individuals with visual or hearing-related impairments and two drivers diagnosed with ADHD. These sessions explored participants' perception of the HMI mock-ups together with their views on automated vehicles, including ethical considerations, regulatory expectations, acceptance and usability. Eleven of the twenty participants (55%) presented one of these impairments or conditions, ensuring that design conclusions would not default to an unimpaired baseline. Participants were assigned to one of three use-case conditions: UC-Aa (collective perception in shared urban spaces, n = 8, exclusively older adults aged 65+, five with MCI), UC-Ab (collective decision-making in semi-urban roundabouts, n = 6,

the most age-heterogeneous group, 18–64 years), and UC-B (cooperative highway scenarios with a Take-Over Request sequence, n = 6, the most profile-diverse group, combining MCI, ADHD, visual impairment and cultural driving-context diversity). Automation experience varied widely and was shaped as much by infrastructure and geography (several participants noted that lane markings and traffic conditions in their home countries made existing automation features unusable) as by personal preference.

Study design and instruments. Each session lasted approximately 45–60 minutes and followed a chronological, mixed-methods protocol. After a welcome and consent step, participants completed (1) a pre-interaction questionnaire capturing baseline trust, prior AV experience, conditional (ethical/legal) trust, preferred communication modalities and data-sharing attitudes; (2) a mock-up interaction phase, exposing participants to the HMI concept for their assigned use case; (3) a semi-structured interview with guiding questions, capturing spontaneous qualitative feedback immediately after exposure; (4) a post-interaction questionnaire, measuring post-exposure trust, perceived control, information-density and modality preferences; and (5) a brief sociodemographic questionnaire. The instruments were developed and reviewed collaboratively across the consortium to ensure accessibility across all participant profiles and consistency across the three use-case conditions.

Data analysis. IDIADA sessions (Teams, recorded with consent, protocol approved by_IDIADA legal department approval) and Greek sessions (CERTH Ethics Committee approval, ref. 027957; written consent, with comprehension confirmed for MCI participants) were transcribed, checked against recordings, and pseudonymised by participant code. Transcripts were coded by the experimenter using thematic analysis (Braun & Clarke, 2006): themes were reported with participant counts, illustrative verbatims, and suggested improvements. Resulting recommendations were ranked by criticality, converted into design guidelines, and cross-referenced with regulations and the state of the art, yielding 43 final requirements. Data were processed under GDPR (recordings deleted post-transcription; pseudonymised transcripts retained until project end).

Use cases and interview protocol. Three representative use cases anchored the protocol, each associated with a distinct automation level, HMI mock-up and user-story briefing read to participants before exposure.

UC-Aa—Set in urban shared spaces and roundabouts under SAE Level 1/2, where the driver remains the primary operator, the system perceives and predicts the behaviour of surrounding road users—including vulnerable road users and persons with disabilities—by fusing onboard sensors with V2X data. The HMI communicates hidden hazards and driver-distraction alerts through audio and visual channels.

UC-Ab—Extending the shared-space context to high automation (SAE Level 4), the vehicle autonomously handles perception, prediction and decision-making in semi-urban roundabouts, including emergency-vehicle priority negotiation, using V2V/V2I cooperation and combined Hybrid Intelligence/Human-Like reasoning.

UC-B—Set on the highway in a merging context across SAE Levels 3–4, this is the only use case involving a formal Take-Over Request (TOR), e.g., at a planned transition at the end of the ODD: the system prompts the driver to resume control within a defined time window, communicated through a dedicated driver/operator display supported by V2V cooperation.

Table 1: Study population per use case.

Use Case	Automation Level	n	Age Range	Notable Profiles
UC-Aa — Shared spaces	L1/L2	8	65+	MCI (5), hearing impairment (1), experienced driver (1), Older driver (1)
UC-Ab — Roundabouts	L4	6	18–64	Experienced drivers (5), novice driver (1)
UC-B — Highway / TOR	L3/L4	6	25–35 (+1 older)	ADHD (2), MCI (1), visual impairment (1), AI expert (1), Experienced driver (1)

RESULTS PER PROFILE

Thematic analysis of the interview transcripts, cross-referenced with post-exposure questionnaire data, produced convergent and profile-specific findings across the three use cases. Participants with MCI consistently reported information overload and could not reliably identify the priority action during a warning event, consistent with Wickens' (2002) Multiple Resource Theory and the reduced processing speed and selective attention documented in cognitive ageing (Park and Reuter-Lorenz, 2009). They required explicit motor directives ("BRAKE NOW") rather than descriptive hazard labels, an extended warning lead-time, and a persistent spatial overlay linking the warning to the hazard's location. Despite these issues, MCI participants uniformly valued the combination of a full-width red banner, audio alert and explicit action directive, and the visible detection of hidden hazards was a strong trust anchor across this group.

Older adults, evaluated primarily in UC-Aa, reported residual ambiguity about whether the vehicle or the driver was expected to act, and requested a persistent, always-visible automation action-state indicator together with a predictive hazard visualisation. Onboarding to establish an accurate mental model of partial automation was identified as a specific need for this group.

Participants with hearing impairment could not rely on the audio channel and required the visual display, supported by mandatory haptic feedback, to carry the full alerting load; text below a minimum size and contrast threshold was reported as unreadable under time pressure. The participant with visual impairment similarly required larger text, higher contrast and automatic voice read-out of critical messages, together with additional processing time before Take-Over Request deadlines. Participants with ADHD, evaluated in UC-B, reported that they missed the Take-Over Request warning on first presentation or noticed it only at the last moment, which is consistent with the attentional difficulties documented in drivers with ADHD (Barkley, 2004;

Barkley & Cox, 2007). A staged warning cascade, an early ambient cue, followed by a preparation stage, followed by an explicit action command, was identified as the design response best matched to this attentional profile, and was independently requested by the novice driver (UC-Ab) for the same underlying reason: unfamiliarity with the interface removes any learned scanning pattern that could otherwise compensate for a single, late warning.

Experienced drivers, evaluated primarily in UC-Ab and UC-B, requested different information: standard vehicle telemetry alongside AV-specific displays, a remote-operator fallback channel, and an optional "detailed" or "expert" mode with expanded data layers, possibly reflecting the cognitive bandwidth freed once the driving task itself is automated. One participant's trust score dropped to the most extreme negative value recorded in the study following a single trajectory-rendering misalignment, illustrating how a single salient system failure can immediately and disproportionately erode trust regardless of prior positive exposure (Lee and See, 2004). Across every profile, three findings were shared. First, multimodal warning delivery was unanimously preferred and, for hearing-impaired participants, functionally necessary rather than optional. Second, a graduated colour semantic (blue/amber/red) was intuitively understood across cognitive and sensory profiles, making it a strong candidate for standardisation. Third, **role ambiguity** about who is acting - not knowing whether the vehicle was already acting or whether the driver was expected to intervene - was systemic, appearing across all three use cases (in UC-Ab, as uncertainty over whether any intervention was expected, suggesting an inaccurate mental model of Level 4) and all participant profiles irrespective of cognitive or sensory status; it constitutes the single most consistent design failure identified in the study. This finding was most severe during the Take-Over Request sequence in UC-B, where hesitation was reported by all six participants in response to a direct question asking whether they had hesitated or not, and required action ("BRAKE NOW") was correctly identified by only one participant (17%) who was an experienced driver and Expert AI on first exposure.

Table 2: Cross-profile summary of key interview-derived recommendations.

User Profile	Key Issue Observed	Priority HF Recommendation
MCI	Information overload; role ambiguity	Suppress non-critical elements; explicit motor directive; extended warning lead-time
Older adults	Automation-state ambiguity	Persistent action-state display; predictive hazard overlay
Hearing impairment	Audio channel unavailable	Mandatory haptic feedback for all warnings; visual channel carries full load
Visual impairment	Small text; insufficient processing time	Larger text; ≥7:1 contrast (WCAG 2.x AAA, above the ISO 15008 baseline); automatic voice read-out; extra time before TOR (n = 1).
ADHD / novice drivers	Missed or late-noticed warnings	3-stage cascade (aware → prepare → act); animated attention-getter
Experienced drivers	Missing telemetry; trust broken by rendering error	Standard telemetry display; validated trajectory rendering; optional expert mode

SUMMARY OF RECOMMENDATIONS AND NEXT STEPS FOR FUTURE WORK

The interview findings were translated into 43 interview-derived HMI requirements (Hentati et al., 2026, in press), distributed across the three use cases and the participant profiles described above. Four cross-cutting recommendations summarise this body of work.

Explicit action-state communication. The HMI shall continuously and unambiguously state whether the vehicle is acting or whether the driver is expected to act ("Vehicle is braking" vs. "You must brake"). This single change addresses the most systemic finding of the study.

Progressive, staged disclosure. During any warning or Take-Over Request event, non-critical display elements shall be suppressed (two participants suggested a maximum of three concurrent on-screen elements), and time-critical communication shall follow a staged cascade (an early awareness cue, a preparation message, and an explicit action command) rather than a single late warning.

Mandatory multimodality with profile-adaptive defaults. No safety-critical message shall be conveyed through a single channel; visual, auditory and haptic redundancy shall be the default (the same message on each channel, not additional content), with information density adaptable to profile (e.g., "minimal" density as a default for MCI profiles, "detailed" mode available on request for experienced users).

Accessible, spatially-anchored hazard communication. Warning text shall meet a minimum size and contrast standard with automatic voice read-out available, and hazard information shall be spatially anchored to the road view (arrow, highlighted zone, or predicted trajectory) rather than communicated through text alone.

These interview-derived requirements provide a traceable, evidence-based foundation for the next phase of the project, in which the three use cases will be implemented as working HMI concepts and the recommendations above incorporated into their design.

LIMITATIONS

Several limitations constrain the generalisability of these findings. First, static mock-ups (rather than dynamic, interactive interfaces) were used, and trust was measured with a single pre/post item rather than a validated questionnaire, for time reasons. Second, the sample is small (n = 20; 6–8 per use case) and recruited via convenience/purposive sampling, with uneven profile distribution across use cases (e.g., ADHD only in UC-B, MCI mostly in UC-Aa), confounding profile and use-case effects; interviews were also conducted in different languages/countries by different interviewers. No formal statistical inference was performed, so results should be read as indicative, hypothesis-generating patterns rather than confirmed effects. The next project phase will address these gaps: implementing the three use cases as working HMI prototypes will generate the behavioural data needed for genuine pass/fail acceptance criteria, refine per-profile knowledge gaps, and be complemented by larger dynamic simulator studies and real-world pilots to confirm or revise these patterns.

CONCLUSION

Following ISO 9241-210:2019, the first cycle of an iterative UCD process was applied across three automated-driving use cases, engaging twenty participants reflecting diverse user profiles rather than a single "average" driver. The results show a pattern of conditional acceptance: participants did not reject the proposed HMI concepts, but consistently identified specific, implementable design deficiencies tied to their individual cognitive and sensory profiles. Multimodal alert feedback and a graduated blue/amber/red colour semantic were preferred and understood across profiles, including neurodiverse participants, supporting their consideration for standardisation. Conversely, a 100% (6/6) self-reported hesitation rate and a 17% (1/6) comprehension rate during Take-Over Requests in UC-B, together with the systemic role-ambiguity finding present across all three use cases, identify explicit action-state communication as a safety-critical redesign priority rather than a usability refinement. The 43 interview-derived requirements produced by this work provide a traceable, evidence-based foundation for the HMI concepts to be implemented and validated in the next, use-case-driven phase of the AIGGREGATE project, ensuring that inclusivity is designed in from the outset rather than retrofitted after the fact.

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