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Original
A Review of Automotive AR-HUD Interfaces Across Driver Roles and Vehicle Automation Levels / Vezzani, L., Strada, F., Bottino, A.. - In: IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS. - ISSN 1558-0016. - ELETTRONICO. - 27:5(2026), pp. 5024-5044. [10.1109/TITS.2026.3657505]

Publisher:
IEEE

Published
DOI:10.1109/TITS.2026.3657505

A Review of Automotive AR-HUD Interfaces Across Driver Roles and Vehicle Automation Levels

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***Abstract*—Augmented Reality Head-Up Displays (AR-HUDs) have emerged as a transformative technology in the automotive sector, significantly enhancing driver awareness and safety by seamlessly integrating critical information into the driver's direct line of sight. However, implementing effective AR-HUD systems presents several challenges, including designing intuitive yet minimally distracting user interfaces, ensuring accurate spatial registration, and adapting visualizations to different contexts and levels of vehicle automation. This article provides a comprehensive overview of the current literature on automotive AR-HUDs and offers a structured taxonomy that classifies existing studies along two main dimensions: the specific features of the AR-HUD interface, which capture the relationship between display-related and interaction-related characteristics across tasks and driving contexts, and the human-automation roles, which frame the evolving shift of control, attention, and responsibility between the human and the automated system as vehicle autonomy increases. Additionally, we critically analyze existing testing methodologies and identify significant gaps, such as the overreliance on testing in virtual environments and the lack of standardized frameworks for the progressive evaluation of AR-HUD interfaces, from conceptual designs to immersive virtual simulations and real-world assessments. We conclude by discussing key open research questions and future research directions needed to overcome current limitations and realize the full potential of AR-HUD technology.**

***Index Terms*—Head-up displays, Augmented Reality, Autonomous Driving, User Experience, Human-Computer Interaction.**

I. INTRODUCTION

Despite the increasing use of advanced driver assistance systems and improved road infrastructure, human error is still the main cause of over 90% of all road accidents [1], [2]. Drivers often overlook important information such as road signs, speed limits or hazards, especially in complex environments or when they are distracted by accessory tasks [3]. Technologies that help drivers maintain their concentration and situational awareness are therefore essential for improving road safety.

One such technology is Head-Up Displays (HUDs), which project relevant information such as speed, navigation instructions, or warnings into the driver's field of view (FOV), allowing them to keep their eyes on the road [4]. This technology was originally developed for aviation, specifically for the development of Enhanced Flight Vision Systems, which combine infrared or visible light sensors with a HUD to improve pilots' situational awareness in low visibility conditions [5]. These systems have demonstrated the value of integrating visual data into the pilot's line of sight without increasing cognitive load and have therefore inspired their adaptation to the automotive sector [2].

Fig. 1: AR-HUD concept by Stradvision [9] showing spatially registered warnings (maneuver suggestion, collision warnings) together with non-registered informational elements (navigation instruction, dashboard information).

Conventional automotive HUDs typically project 2D graphic elements (GEs) onto fixed positions on the windshield. These GEs are spatially decoupled from real-world objects, which can affect their intuitiveness and in some cases lead to distractions as users have to mentally align the virtual overlays with the external scene [6], [7]. Augmented Reality Head-Up Displays (AR-HUDs) were developed to overcome these limitations. Unlike conventional HUDs, AR-HUDs spatially register GEs [8], such as navigation arrows or hazard indicators, with the corresponding elements in the external environment so that, when displayed, they appear as an integrated part of the driver's view of the road (Fig. 1).

This spatial coherence is achieved through a combination of real-time processing, sensor fusion, display technologies, transparency management, color correction and geometric distortion correction [10], [11]. The result is a visual experience where digital information blends seamlessly with the physical world, improving the driver's situational awareness and reducing the cognitive effort required to interpret the user interface [12]. AR-HUDs have been shown to increase the clarity of navigation instructions [13], improve pedestrian perception [14], and enable better recognition of surrounding vehicles [15]. Also, recent applications have been proposed for driver training [16] and entertainment [17].

The combination of virtual and physical elements in AR-HUDs brings with it a number of technical and human-centered challenges that extend beyond those of traditional HUD systems. AR-HUDs require precise real-time spatial registration to ensure that virtual content is accurately aligned

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with external objects despite varying lighting, occlusions and viewing angles [18]. In addition, the system should dynamically adapt to different driving contexts and levels of vehicle automation while maintaining user trust and minimizing cognitive overload [19]–[21]. Furthermore, several factors influence the usability and acceptance of AR-HUDs, including the placement of the display, the information density and the visual design of the graphical elements [22]. Seamless integration with existing vehicle systems is also critical to ensure visual continuity with dashboards and infotainment displays and to support personalization of the user interface based on user preferences and situational context [23].

Given the growing interest in AR-HUDs in the automotive industry, this article aims to offer a comprehensive, structured, and up-to-date review of the field, focusing on the unique challenges, interaction mechanisms and implementation aspects that characterize AR-HUDs' role across different levels of vehicle automation and driver responsibility.

This review builds on the seminal work in [24], which examined the research available up to 2014, and in [25], which analyzed the studies conducted up to 2017. More recent reviews focus on specific aspects such as AR-HUD display properties [26], take-over requests [27], [28], interactive automotive applications [29] or external human-machine interaction [30]. The most recent comprehensive review of AR-HUDs is [31], which surveys studies on AR-HUDs in automated driving and handover scenarios, focusing on safety, driver performance, and user experience. Although these studies provide valuable insights, they address technical and human-factors aspects separately and lack an integrated framework connecting AR-HUD display characteristics with their interaction role across different levels of automation.

To address this gap, this review systematically maps the literature through two complementary dimensions: (i) the features of the AR-HUD interface, which captures the relationship between display-related and interaction-related characteristics across task and driving contexts, (ii) the evolving Human–Automation Roles (HAR), which describe how control, attention, and responsibility shift between the human and the automated system as vehicle autonomy increases. Through this dual perspective, detailed in Section IV, we (i) link technical and human–interaction perspectives in a unified analysis, (ii) highlight design and usability challenges, and (iii) identify open research problems and future directions for safer, more intuitive, and context-aware AR-HUD systems. This integrated view connects technical design factors with human factors and interaction processes, illustrating how different AR-HUD features can support the occupant as their role shifts from *active driver* to *passive user*.

The remainder of this paper is organized as follows. Section II presents the review methodology. Section III provides an overview of the technological foundations and current limitations of automotive AR-HUD systems. Section IV introduces the proposed taxonomy. Section V discusses the testing environments used in the literature and their methodological implications. Sections VI, VII, and VIII analyze the reviewed studies according to the categories of our primary taxonomy dimension. Section IX summarizes the main open research challenges and future directions, and, finally, Section X concludes the paper.

II. METHODS

To ensure the relevance, transparency, and reproducibility of the review process, this study was conducted in accordance with the PRISMA 2020 guidelines for systematic reviews [32]. The methodology was designed to systematically identify, screen, and select relevant studies addressing automotive AR-HUDs, while allowing for a structured refinement of the search strategy before the screening phase, in line with PRISMA recommendations.

Four eligibility criteria (ECs) were defined a priori, before database querying, to guide study inclusion:

EC1 - Peer-reviewed journal articles, conference proceedings, or white papers presenting original research or structured reviews.
EC2 - Publications written in English.
EC3 - Studies published between January 1, 2007, and March 1, 2025.
EC4 - Studies explicitly addressing AR technology integrated into in-vehicle HUDs, including system design, implementation, interaction modalities, usability, safety, cognitive workload, or overall driving experience.

The literature search was performed across four major scientific databases: IEEE Xplore, ACM Digital Library, ScienceDirect, and SpringerLink. Additional peer-reviewed databases were consulted using Google Scholar to supplement the retrieved results. The search was conducted between December 2023 and April 2025.

The search strategy was defined and refined following PRISMA recommendations, with an initial set of search strings specified to capture the core aspects of AR-HUD research. To ensure adequate coverage of the multidisciplinary nature of the field, the final strategy consisted of five search strings (RS-I to RS-V), targeting complementary thematic areas related to AR-HUD technologies, human–machine interaction, automation, design principles, and context-aware adaptation.

An initial research string (**RS-I**) was used to identify the main body of AR-HUD literature and recurring terminology. Based on the analysis of retrieved records and consistent with PRISMA-guided refinement practices, four additional research strings were defined to systematically expand coverage across key thematic dimensions identified in prior reviews and seminal works [24]–[26], [31], [33]. We defined four additional research strings to cover the following recurring thematic areas: **RS-II** explores the relationship between AR-HUDs and automated vehicles; **RS-III** retrieves papers on human interaction with AR-HUDs focusing on common interaction modalities in AR-HUDs and related HMI requirements; **RS-IV** targets established design principles, practices and framework for AR-HUDs; and **RS-V** investigates context-aware display adaptation. Below, we report the complete set of research strings and the synonyms used (Table I):

RS-I - *("HUD" AND "AR" AND "automotive")*
RS-II - *("AR" AND "HMI" AND "AV")*

RS-III - *("AR-HUD" AND ("driver interaction" OR "eye tracking" OR "gesture recognition"))*
RS-IV - *("AR-HUD" AND "design guidelines")*
RS-V - *("AR-HUD" AND "adaptive" AND "driving scenario")*

Key term	**Synonyms**
HUD	head-up display, windshield, windscreen
AR	augmented reality, AR overlay
AR-HUD	augmented-reality head-up display, augmented-reality HUD, windshield AR-HUD
design guidelines	design framework, design principles, interface guidelines, HMI framework
driver interaction	driver–vehicle interaction, UX
eye tracking	gaze, gaze tracking
adaptive	context-aware, context-aware interface
driving scenario	driving context, road environment
HMI	human-machine interaction, in-vehicle interface
AV	autonomous vehicle, autonomous driving

TABLE I: Key terms and synonyms used in the search strings.

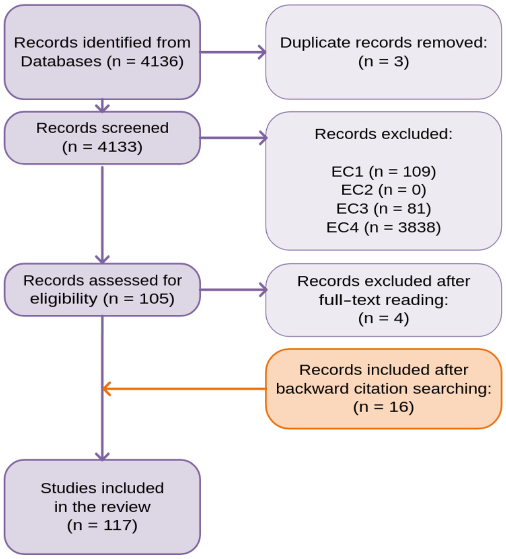


Fig. 2: PRISMA flow diagram, including backward citation results.

The database search yielded a total of 4,136 records, which were imported into Zotero for reference management. After duplicate removal, 4,133 records were screened, independently by two reviewers, based on titles and abstracts, leading to the exclusion of 4,028 studies. The remaining 105 articles underwent full-text assessment for eligibility, resulting in the inclusion of 101 studies from the database search. Backward citation searching was then performed on the selected papers, identifying an additional 16 relevant publications. Overall, 117 studies were included in the final review.

Disagreements at each stage of the screening and selection process were resolved through discussion, and a third reviewer was consulted when consensus could not be reached. The complete identification, screening, eligibility, and inclusion process is summarized in the PRISMA flow diagram shown in Fig. 2.

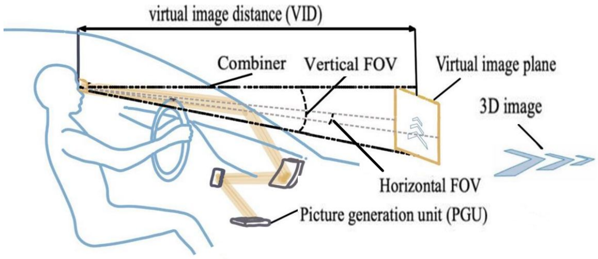


Fig. 3: Key elements of HUDs and their position in relation to the driver. Image adapted from [34].

III. AR-HUD TECHNOLOGIES AND LIMITATIONS

Before delving into the core topics of this survey, we briefly outline the technical foundations of AR-HUD systems since the visual quality, reliability and overall user experience of these interfaces are strongly influenced by the underlying hardware architecture and optical characteristics. The recent comprehensive review by Zhou et al. [34] emphasizes the technological advances in optical and display components, but also highlights the current limitations in seamlessly integrating virtual content and the real-world environment. In the following, we summarize the key technical concepts and challenges for AR-HUD and refer interested readers to the original paper for further details.

A. Projection and Optical Systems

The optical architecture of an AR-HUD plays a critical role in the perceived quality of the display and its integration into the vehicle windshield. At the heart of this system is the Picture Generation Unit (PGU), which creates the virtual content that is projected into the driver's line of sight. This content is then relayed through an optical combiner that superimposes the image over the external driving scene (Fig.3).

However, creating a truly immersive and intuitive AR-HUD faces two fundamental optical challenges: (i) achieving a wide FOV, and (ii) accurately displaying virtual content at multiple depths.

The first challenge is rooted in a difficult trade-off between the display size and other critical factors like image brightness and optical artifacts. This issue was particularly evident in early AR-HUD systems, which used freeform mirrors as optical combiners [34]. While functional, they struggled to provide a large FOV without making the physical assembly large and cumbersome. To address these packaging limitations, modern designs increasingly leverage waveguide optics, which use thin, transparent elements to enable more compact and flexible HUD integration [34]. While this technology solves the problem of size, the fundamental challenge with the FOV itself remains. Consequently, most current commercial and experimental AR-HUDs are limited to a FOV that rarely exceeds 20° [34]. This inherent limitation means that today's systems are effectively "small-area" displays that project content onto a constrained portion of the windshield (Fig. 4, *Top*). In contrast, the ultimate vision is the "full-windshield" display that seamlessly covers the driver's entire view (Fig. 4, *Bottom*). Due to current technological immaturity, however,

Fig. 4: *Top:* small HUD displaying small images and text on the bottom of the windshield. *Bottom:* full windshield HUD displaying a bounding box matching the position of a pedestrian crossing the road. Images adapted from BMW website and [35], respectively.

such expansive displays are primarily explored in research using virtual and simulated environments, as can be seen for instance in [35].

The second key challenge is displaying content at multiple perceived depths, a fundamental requirement for correctly anchoring virtual graphics to real-world objects at varying distances. This requires the management of multiple optical paths [36], [37] and the integration of focus-tunable elements, such as varifocal lenses [37]. Although various solutions have been proposed, no universally optimal approach has yet emerged, as highlighted in [34], [36]. In addition to technical issues, integrating virtual and physical elements in AR-HUDs introduces human perceptual issues, such as visual discomfort and misalignment between real and virtual cues [38], which require careful ergonomic and optical design. Among these, the *vergence–accommodation conflict* is particularly significant: it occurs when the eyes converge on a distant virtual object while accommodating to the fixed optical distance of the display, potentially causing eye strain and reduced depth perception [39]. Furthermore, incorrect depth alignment between virtual elements and real objects can cause errors in spatial judgment, while rapid switching between multiple depth planes can create an unstable visual experience [34].

B. Spatial Registration and User Point of View

Alongside the optical architecture that defines the visual quality of an AR-HUD, a second critical component is *spatial registration* that is the precise, real-time alignment of virtual content with the driver's view of the world. Achieving this alignment is a complex task. It requires the system to track the driver's eyes (often using dedicated cameras or smart glasses), estimate the vehicle's position, build a model of the external environment, compensating for parallax and latency in real time [40], [41]. This can be achieved using technologies such as *eye tracking cameras* mounted on the vehicle, as used by Maag et al. [7]; or *eye tracking glasses* worn by the driver, as used by Merenda et al. [42]. Underpinning these dynamic processes is a robust calibration procedure. This calibration must account for static variables, such as the windshield's curvature and differences between vehicle models, as well as user-specific parameters like the interpupillary distance. Although many systems rely on static factory calibration or manual adjustments, more advanced implementations are beginning to incorporate self-calibration mechanisms using depth cameras or sensor fusion [41].

While these user-centered calibration procedures are essential for aligning virtual content from the driver's perspective, they must be complemented by an accurate understanding of the external environment in which the vehicle is operated [40]. Recent advances in sensing technologies – such as high-resolution RGB cameras and LiDARs – have significantly improved the ability to track and map dynamic environments. These two primary sensors offer a complementary set of capabilities and trade-offs. LiDAR technology excels at providing highly accurate 3D depth information, allowing it to create a precise structural map of the environment. However, its primary drawbacks are its significant performance degradation in adverse weather conditions, such as heavy rain or fog, and its relatively high cost. In contrast, RGB cameras are inexpensive and capture rich color and texture information, which is vital for object recognition. They struggle, however, to infer reliable depth information on their own and are similarly susceptible to poor visibility in adverse weather, in addition to visual artifacts common in driving, such as motion blur from vehicle vibrations and lens flare from intense lighting sources [43].

Data from other vehicle systems can supplement this environmental model. For example, radar is robust in all weather but offers low spatial resolution, while the Global Navigation Satellite System provides location data that can be unreliable in urban canyons or tunnels due to signal shadowing.

Given the individual limitations of each technology, an ideal environment tracking system should rely on sensor fusion. By intelligently combining the accurate depth from LiDAR, the rich context from cameras, and supplementary data from other sensors, the system can create a single, more reliable model of the world [44].

C. Adoption Status

Despite substantial research progress and growing industry interest – with active developments from companies such as Envisics [45], Huawei [46], Valeo [47], Nippon Seiki [48] and Texas Instruments [49] – fully spatially registered AR-HUDs, as defined in this survey, remain uncommon in mass-produced vehicles. Marketed systems such as the Volkswagen ID.3 and ID.4 models [50] (Fig. 5, Left) and the Mercedes S-Class [51] (Fig. 5, Right) provide perspective-consistent, lane-relative

Fig. 5: *Left:* an example of AR-HUD from Volkswagen, highlighting the lane and the vehicle preceding; *Right:* AR-HUD interface from Mercedes, with chevrons indicating a left turn.

wayfinding graphics projected into the driver's field of view. However, publicly available sources from Volkswagen [50] do not explicitly reference real-time spatial registration, while those from Mercedes [52] allude to anchored content without disclosing technical details of its implementation. The lack of technical information and the resulting ambiguity preclude a rigorous assessment of these commercial systems preventing their inclusion in our review.

IV. TAXONOMY DEFINITION

To systematically analyze design goals, technical challenges, and evaluation strategies in the AR-HUD literature, we developed a structured taxonomy that captures recurring themes, supports the identification of research gaps and informs future developments in this field.

AR-HUDs exhibit a "dual nature" spanning two tightly coupled dimensions. First, from a *technical* perspective, they operate as display systems whose optical architecture, luminance, field of view, and registration accuracy determine how seamlessly virtual and physical contents are combined and visualized. Equally critical, from a *human–interaction* perspective, they serve as adaptive, context-aware human–machine interfaces that mediate information exchange between the occupant and the vehicle under different automation conditions. Recognizing this dual nature is essential to understanding how AR-HUD technologies must evolve to simultaneously preserve perceptual coherence while supporting effective and adaptive interaction.

Previous reviews have typically examined the technical and interactive aspects of AR-HUDs in isolation, focusing either on visual components [34], [36] or on human–factors outcomes [28], [29], [31]. Our taxonomy addresses this gap through a *features* dimension (Table II) that captures how display-related and interaction-related characteristics co-evolve, examining *what content* is presented, for *what purpose*, and *how it adapts* to user and driving context.

However, understanding AR-HUD effectiveness requires a second critical perspective: how the human's role and interaction needs fundamentally change across automation levels. This second aspect, largely absent from existing reviews, is addressed by introducing a *human–automation roles* dimension (Table III), which describe how the human's responsibility and interaction needs vary with different levels of vehicle automation.

A. Features

The primary taxonomy dimension classifies the studies based on specific AR-HUD **features**, focusing on the design, functional, and adaptive characteristics of the system – that is, how information is represented through visual elements, for what purpose it is provided, and how it adjusts to the driver and driving context. It includes three main categories (Table II): **Graphic Elements**, **Purpose**, and **Adaptability**. Each category was identified inductively from recurring concepts found during the full-text analysis of the selected studies, through iterative coding and author cross-validation.

Graphic Elements (GEs) refer to the visual components displayed by the AR-HUD. For consistency throughout the taxonomy, we distinguish between two main groups (discussed in detail in Section VI): **AR-based graphics elements (ARGEs)**, which are spatially registered with the external environment, and **non-AR-based graphics elements (non-ARGEs)**, which are screen-fixed graphical components without spatial registration.

The categories of **Purpose** and **Adaptability** capture, respectively, the functional goals of the AR-HUD content (that is the high-level *why* behind the displayed information) and the degree to which the interface dynamically adapts to the driver's state (e.g., attention, workload, or preferences) or the surrounding driving context (e.g., traffic conditions, visibility, or automation level). *Purpose* category consolidates recurring objectives such as safety enhancement, wayfinding, and trust establishment, while *adaptability* encompasses adaptive behaviors dependent on the driver and/or the environment.

B. Human–Automation Roles

Complementing the *features* dimension, the second taxonomy dimension focuses on **human–automation roles (HAR)**, which characterize how the driver's responsibility and interaction demands evolve with increasing vehicle automation. This dimension provides the human-centered counterpart of the taxonomy, linking the progression of automation to corresponding changes in attention, control, and situational awareness requirements.

The HARs are conceptually informed by the SAE levels of driving automation [146]. According to the SAE standard, *driving automation* refers to the system's capability to perform all or part of the *Dynamic Driving Task (DDT)*, that is, vehicle motion control, environment monitoring, fallback performance, and operation within a defined *Operational Design Domain (ODD)*. Each of the six SAE levels (0–5) specifies a distinct allocation of responsibility between the human driver and the automated system in executing the DDT.

Since our analysis focuses on interaction and perception rather than the technical decomposition of the DDT, we reinterpret these levels in terms of three broader HAR that describe distinct modes of human involvement and responsibility:

- **active driver (SAE 0–2):** the human performs the full DDT, continuously responsible for vehicle control and environment monitoring, while automation provides limited assistance such as lane keeping or adaptive cruise control.

HUD Features		**Graphical Elements**	
		ARGEs	**Non-ARGEs**
Purpose	Safety	[6], [7], [14], [18], [24], [25], [35], [40], [42], [44], [53], [53]–[81]	[4], [40], [53], [82]–[89]
	Wayfinding	[2], [6], [12], [13], [24], [58], [67], [71], [80], [85], [90]–[94]	[7], [72], [73], [95], [96]
	Non-Driving Related Tasks	[13], [63], [97], [98]	[99]–[106]
	Take-Over Requests	[21], [44], [74], [98], [107]–[112]	[27], [28], [103], [105], [113]–[126]
	Creating Trust	[19]–[21], [68], [78], [127]–[133]	
Adaptability	Driver Dependent Adaptability	[10], [25], [40], [54], [67], [68], [134]	[28], [134]–[136]
	Environment Dependent Adaptability	[6], [35], [62], [80], [85], [90], [134], [137], [138]	[72], [134]

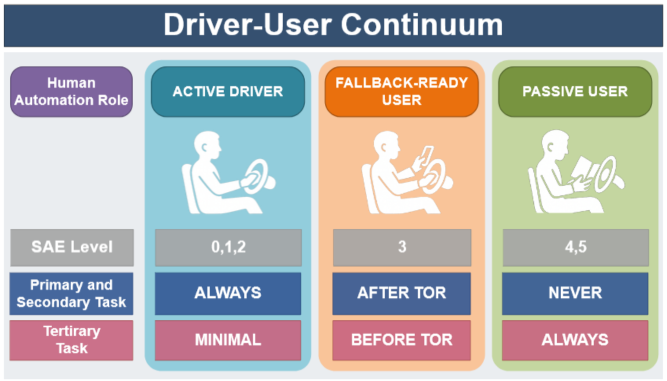
TABLE II: Classification of the reviewed studies within the *Features* dimension of the AR-HUD taxonomy (Section IV-A). The table shows how studies intersect across the **Purpose** and **Adaptability** categories (detailed in Sections VII and VIII), considering their use of **AR-based** (ARGEs) and **non-AR-based** (non-ARGEs) **Graphic Elements** (defined in Section VI), highlighting how different visualization strategies, functional goals, and adaptive mechanisms co-occur in the literature.

Tasks	**Human-Automation Role**		
	active driver	**fallback-ready user**	**passive user**
Primary and Secondary	[2], [4], [6], [7], [10], [12], [14], [15], [18], [24], [25], [33], [35], [40], [42], [44], [53]–[63], [63]–[67], [69]–[73], [75]–[87], [89]–[96], [100], [101], [106], [112], [124], [136]–[144]		
TOR		[21], [27], [28], [63], [74], [98], [103], [105], [107]–[125], [135]	
Tertiary	[13], [88], [89], [99]	[74], [108], [117]	[19], [68], [97], [102], [104], [108], [118], [126], [128], [134], [145]

TABLE III: Studies classified based on the Task investigated and their role according to the *HARs*.

- **fallback-ready user (SAE 3):** the system performs the complete DDT within specific conditions, but the human supervises passively and must re-engage upon request when the system reaches its operational limits.
- **passive user (SAE 4–5):** the system performs all aspects of the DDT, and the human occupant is disengaged from driving tasks; Levels 4 and 5 differ only in the extent of the ODD within which full automation is achieved.

Although defined as discrete categories, the HAR can be interpreted along a descriptive *driver–user continuum* that illustrates how human engagement and task focus evolve with increasing automation, from active control to conditional supervision and, ultimately, full delegation (Fig. 6). Along this continuum, human activity progressively shifts from *primary tasks* (e.g., direct vehicle control such as steering or braking) and *secondary tasks* that assist driving (e.g., signaling or monitoring alerts), to *tertiary tasks* such as infotainment, communication, or other non-driving activities that dominate at higher automation levels. A critical transition point within this spectrum occurs during *Take-Over Requests (TORs)*, when the human must rapidly regain control after periods of reduced engagement. This dynamic progression captures the evolving balance between attention, responsibility, and cognitive workload across the three HAR, offering a human-centered basis for analyzing how AR-HUD features should adapt to different automation contexts (Table III).



Human Automation Role	ACTIVE DRIVER	FALLBACK-READY USER	PASSIVE USER
SAE Level	0,1,2	3	4,5
Primary and Secondary Task	ALWAYS	AFTER TOR	NEVER
Tertiary Task	MINIMAL	BEFORE TOR	ALWAYS

Fig. 6: Representation of the *driver–user continuum* and its correspondence with human–automation roles.

C. Role of Testing Environments

In addition to the two main dimensions of our taxonomy, we introduce the **Testing Environment** (TE) as a critical contextual factor that shapes how AR-HUD systems are assessed and understood. By TE, we refer to the physical or simulated context in which AR-HUDs are tested, from laboratory studies and driving simulators to on-road experiments. Although TE itself is not a classification axis of the taxonomy, it plays an essential role in understanding the results and limitations associated with each dimension analyzed. For this reason, we begin our analysis with an overview of TE. This allows us to better contextualize the evidence reported in the literature, highlight methodological limitations, and clarify how different TEs support (or limit) the assessment of specific AR-HUD dimensions.

Therefore, our analysis starts by discussing TEs, followed by the discussion of the core dimensions of the taxonomy in the following sections.

V. TESTING ENVIRONMENTS

Integrating new technologies into vehicles requires thorough testing of their features and components to ensure safety, functionality and user satisfaction throughout development. HUDs and AR-HUDs have been widely tested in recent years using various TEs, each offering different levels of realism and immersion, involving different safety considerations, and incurring varying costs in terms of monetary expenses, implementation time, and resource allocation. The main methods mentioned in the literature for evaluating AR-HUDs include: *(i) conceptual evaluation*, *(ii) virtual reality (VR) testing* and *(iii) road testing*.

A. Conceptual Evaluation

Conceptual evaluation involves a non-interactive evaluation approach that uses questionnaires [68], images and videos [134], [147], focus groups and interviews [63] to gather subjective feedback on HUD designs. This method is particularly useful in the early stages of development, when a HUD interface is yet to be implemented, as it gives designers a quick insight into the potential strengths and weaknesses of their HUD concepts [134], [148]. Its primary benefits are its low cost and the rapid acquisition of feedback. This approach allows for comprehensive evaluation of design concepts without the logistical complexity and financial implications associated with more immersive testing methods [149] and enables rapid testing of different implementations while potentially collecting extensive data on them [150], usable for a later implementation.

However, the conceptual evaluation has significant limitations, primarily because participants do not experience the HUD in an interactive or context-rich environment. Without a working prototype or task-based interactions, they are unable to assess the practical functionality of the system, such as how it responds to driver input or supports situational awareness. The lack of task execution also makes it impossible to assess whether the AR-HUD effectively supports the driver in dynamic activities. As a result, key elements such as real-time responsiveness, ease of use and intuitiveness of interaction under variable conditions remain unexplored [120], [134] and evaluations are consequently limited to superficial aspects such as aesthetics or layout preferences [134]. Therefore, while conceptual methods can provide insight into the *hedonic* or *perceptual* attractiveness of AR-HUDs, they are not well suited to evaluate *functional* performance or *technical* feasibility.

B. VR Testing

VR testing provides a controlled, immersive environment for evaluating AR-HUD systems in various VR-based simulators. These simulators vary in complexity, from simple desktop systems [29] to immersive setups with VR headsets [95] and CAVE systems [40]. They can also include physical vehicle mock-ups, ranging from simple steering wheels [124] to complete vehicle chassis mounted on advanced motion platforms, as can be seen in [103], [117], some of which are equipped with physical HUDs of different size, such as those used in [33], [94]. This level of immersion is ideal to overcome the limits of *conceptual testing*. The virtual simulations are managed by a variety of software, including general-purpose game engines such as Unity and Unreal Engine as well as specialized driving simulation software such as SCAnER, which provides a comprehensive toolset for creating detailed and dynamic driving scenarios [62], [70]. These highly versatile tools allow researchers to test different aspects of HUDs features including *GEs* [7], *purposes* [15], and *adaptability* [85].

VR testing offers the unique advantage of safely simulating a wide range of driving conditions, including scenarios that would be impractical or dangerous to recreate in real life. This controlled environment not only ensures participant safety but also allows researchers to thoroughly assess driver interactions with AR-HUDs during critical events, such as vehicle-to-vehicle conflicts [44], [57], encounters with pedestrians [14], and interactions with the vehicle Head-Down Display [4], [102], [125], [151]. In addition, it enables the safe investigation of risky tertiary tasks, such as mobile phone use during assisted driving [117], providing deeper insights into driver behavior. It can also enhance the consistency of measurements aimed at assessing physiological responses during driving tasks (e.g. stress or cognitive load) by reducing uncontrolled environmental noise [44], [66], [79], [105].

Despite its advantages, VR testing faces several challenges. A primary concern is ensuring that simulations not only accurately mirror real-life scenarios but also replicate the complete driving experience, both in the perception of the virtual world and the hazards represented [21]. This fidelity is essential for prompting users to behave as they would in actual driving situations, which is crucial for collecting reliable data on user interactions with HUDs. Therefore, systematic comparisons of simulation data with real-world driving behavior are necessary to validate the effectiveness of VR environments as a testing ground for HUD technologies [152]. Another issue with VR testing is that secondary and driving-related tertiary tasks are often neglected in this TE. This places users in overly simplified scenarios compared to real driving, where drivers usually perform additional interactions (e.g. signaling to other vehicles, adjusting ADAS settings or controlling comfort features), which limits the realism and ecological validity of the simulator. Moreover, participants' behavior may be influenced by the artificial nature of the simulation itself. If they are not properly instructed, the knowledge that they are in a virtual environment – with no real-world consequences – can alter users' emotional engagement and cognitive investment, resulting in behaviors that do not accurately reflect real-world driving patterns [153]. Finally, many VR setups for this type of testing lack motion platforms, which leads to two important problems. First, users do not experience the physical forces involved in real driving, which might reduce the realism of the simulation and limits the generalizability of the data collected [154]. Second, this lack of physical feedback in immersive headset-based setups can increase motion sickness, potentially excluding susceptible participants and biasing the composition of the sample [94].

C. Road Testing

Road testing uses fully functional vehicles to evaluate HUD interfaces in real driving scenarios. This method allows researchers to observe how drivers interact with AR-HUDs amidst the complexity and unpredictability of real-world traffic, road conditions and weather. It also allows participants to experience the system in natural conditions [42]. This provides data that reflects authentic reactions and usage patterns and helps identify problems and benefits that may not emerge in controlled environments [42], [93].

However, on-road testing presents significant issues as well. First, safety concerns limit the types of scenarios that can be investigated. Any malfunction, distraction or delay in the transmission of information could endanger drivers, passengers or other road users [86]. For this reason, on-road studies tend to focus on lower levels of vehicle automation where the driver remains actively engaged in primary tasks and overall control of the vehicle [7], [42]. Testing AR-HUDs in scenarios with higher levels of automation – where users shift to tertiary tasks – is far less common. These contexts pose an additional challenge, as they are difficult to reproduce under real conditions. This is due to the current lack of commercially available SAE Level 4–5 vehicles and the extreme variability of environmental and traffic factors, which limit our empirical understanding the behavior of AR-HUD in these scenarios.

To mitigate these safety risks, road-based evaluations often rely on constrained environments such as parked vehicles [29], [143], [155] or closed test tracks without active traffic [42], [156]. However, the feasibility of such tests depends to a large extent on jurisdiction-specific regulations that are not standardized across countries, which further complicates test planning and limits reproducibility.

Another limitation of road testing is that it is affected by a large number of uncontrollable factors that hinder the possibility of repeating and replicate them exactly across different testing sessions. In addition, collecting comprehensive data in moving vehicles poses further challenges. For instance, biometric sensors should be sensitive enough to capture data even in the presence of vibrations and interferences [157], [158].

D. Use of Testing Methods: Evidence from the Literature

Academic research often favors certain TEs over others when testing HUD interfaces. Of the 115 studies reviewed in this paper, not all included an empirical testing component. Among those that conducted such testing, the majority relied on a single TE type. Within this group of single-TE studies, conceptual evaluation was used 19 times, VR 65 times, and road testing 8 times. Additionally, other 7 studies relied on two TEs, six of them combined VR and Road Testing, whereas only one used conceptual evaluation and VR Testing. This distribution shows a clear preference for VR, while road testing is more limited and mainly reserved for wayfinding [7] and safety enhancement [42] purposes.

This tendency to operate in isolated TEs also highlights a significant gap in research: the lack of a standardized, progressive testing framework. Ideally, concepts and interface features could be explored through conceptual evaluations or focus groups at early stages to enable cost-effective assessments of user acceptance and perceived benefits [97]. VR testing can then simulate dynamic scenarios to assess usability, safety and driver behavior under controlled yet immersive conditions [14]–[16]. Finally, road tests offer the opportunity to validate system performance and contextual integration in real-world environments. Crucially, assessments at each stage of this phased approach should explicitly take into account the actual capabilities and limitations (e.g. spatial registration accuracy, latency and limited FOV) of current AR-HUD technologies. This will ensure that the insights gained are directly applicable to real-world implementations and are not based on unrealistic assumptions about hardware capabilities.

VI. GRAPHIC ELEMENTS

With a clearer understanding of the test environments underpinning HUD research, we begin to explore the elements of our proposed taxonomy in detail by examining the GEs that are fundamental to how AR-HUDs convey information to the driver. AR-HUDs rely on the combination of two main categories of GEs to display information, either AR-based (ARGEs) or not (non-ARGEs). As there is ambiguity in the literature and media about the use of the term AR, we will first clarify how we define ARGEs and non-ARGEs in the context of this article.

A. ARGEs

According to Azuma's definition [8] of AR, we consider ARGEs as digital visual components that are spatially registered with the physical environment and displayed in the driver's FOV in such a way that they appear anchored or integrated with elements of the real world. ARGEs adapt to the surrounding context in real time by matching their position, scale and behavior with the relevant features of the external scene. By leveraging environmental data and sensor fusion, ARGEs provide contextual guidance, such as projecting navigation cues directly onto the roadway [73], [91], [92],

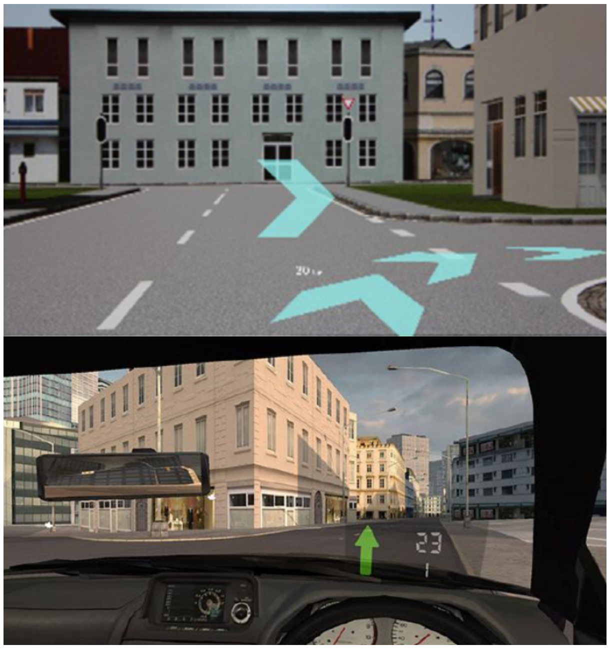


Fig. 7: *Top:* ARGEs using a pathway made of chevrons projected in front of the vehicle indicating the turning direction. *Bottom:* non-ARGEs displaying a green arrow to indicate the direction to follow together with the current speed. Images adapted respectively from [67] and [95]

highlighting pedestrians or visually marking hazards aligned with their actual position [147], [159] (Fig. 7, *Top*). These features improve the driver's focus and situational awareness and enable more intuitive and efficient decision-making [13], [81], [124].

Müller et al. [128] propose a taxonomy for the classification of ARGEs based on four main dimensions: (i) *information type*, which distinguishes dynamic elements (e.g., nearby vehicles [15]) from location-specific data (e.g., road geometry [13]); (ii) *functionality type*, which distinguishes between purely informative elements (e.g., [19]) and those that provide explicit guidance (e.g., [112]); (iii) *content reference type*, which indicates whether AR elements emphasize existing features of the real world [35] or present completely new information [13]; and (iv) *registration type*, which describes how AR elements are arranged on the display with respect to the real-world environment, the vehicle, and the user. Although these dimensions were originally proposed for fully autonomous contexts, they can be extended as well to ARGEs in lower automation levels.

B. Non-ARGEs

By contrast, non-ARGEs refer to graphical components displayed on a portion of the windshield without direct spatial correspondence to the driver's surroundings [86], [88], [100] (Fig. 7, *bottom*). These include icons, that is two-dimensional symbols fixed on the display surface (e.g., speed or warning icons), and spatial indicators, symbolic elements that conceptually represent direction or distance (e.g., floating arrows pointing toward a turn). Previous studies show that these GEs can help reduce the driver's cognitive load by ensuring that important information is easily accessible without overly distracting attention from the road (as reported in [6], [84], [88]). Non-ARGEs are mainly used to visualize data such as vehicle speed [134], vehicle status [105], [126], turn-by-turn directions [13], [22], [67], [95], navigation assistance and routing [7], [13], [33], infotainment controls [59], [77], [102], [103], [136], [160], take-over requests [103], [105], [115], and lateral position monitoring [82].

C. Challenges

It is important to recognize that the same information can be conveyed by both GE types, though through different presentation methods. Each type has distinct advantages, limitations, and design considerations that affect GE effectiveness, driver cognitive load, and system usability [62], [71], [90]. For example, non-ARGEs used to signal pedestrians may distract attention from actual hazards [16], [18], [35], particularly in full windshield HUDs with large display areas [64]. In contrast, small HUDs may struggle to render ARGEs effectively, as optimal cue positions can fall outside the display area, undermining their validity.

Even within the same category, different types of GEs can have a significant impact on the effectiveness of communication. For example, the use of a *virtual shadow* ARGE to highlight pedestrians has been shown to significantly improve situational awareness and almost triple the rate of correct interpretation of pedestrian movements compared to a *bounding box* ARGE [18] (Fig. 8), which risks obscuring parts of the windshield, making the driver less able to perceive the actual pedestrian. Conversely, the *virtual carpet* is an ARGE that is effective in highlighting the direction to follow [92], but it is not able to provide accurate information when its length is used to communicate the vehicle speed [62], [69].

These example-specific effects also reflect a broader trend: ARGEs are most commonly studied as an assistance tool for *active drivers*, where numerous studies have shown that spatially registered visualizations are more effective than traditional non-ARGEs in conveying real-time driving information [7], [13], [92], [94], [161], [162]. In studies involving *fallback-ready users* and *passive users*, the use of ARGEs is more evenly balanced with non-AR elements. This reflects a shift in user role along the *driver-user continuum*: as users become less involved in vehicle control and more involved in supervisory or non-driving activities, the benefits of precise spatial registration may diminish, and simpler, less immersive interfaces may be sufficient or even preferable [102], [135]. Thus, while AR-based support for primary driving tasks and some secondary tasks is relatively well understood, the role and optimal design of ARGEs for secondary and especially tertiary contexts are not yet sufficiently explored and require further investigation.

Regardless of the level of automation or task type it is supporting, the effectiveness of a GE and of the overall AR-HUD heavily relies on their design, which must minimize distractions and support efficient information transfer to enhance both safety and usability [29], [82], [94], [101], [147],

Fig. 8: *Top*: The virtual shadow ARGE indicates the direction of the pedestrian crossing the road as a shadow in front of their feet. *Bottom*: The red bounding boxes highlight the figure of every pedestrian on the curb and crossing the road. Images adapted from [163]

[151]. One critical factor is the transparent nature of HUD displays, which demands careful control of GE's opacity, size, and resolution [164]. Visibility issues also arise under dynamic environmental conditions: for instance, symbols may become indistinct when their color matches the background, such as a red icon blending into a red traffic light [35], [81], [139], [165], [166]. As discussed in Section III, designing ARGEs further requires precise alignment with real-world elements from the user's viewpoint. Then, as the visual complexity of the driving scene increases, designers must also avoid cluttering the windshield, either reducing the number of elements displayed [108] or varying the ARGEs used, for instance changing their color [147]. Indeed, research shows that excessive or poorly placed elements can alter perception [11], [22], [140], reduce interpretability [22], [78], and ultimately increase the risk of errors [18], [65], [94], [140].

In addition, the design of AR-HUD interfaces should consider cognitive ergonomics, as the type, choice, and placement of GEs can significantly impact the driver's workload [89]. When well-designed, these elements can help reduce mental workload in tasks such as navigation [13] and accessing traffic information [80], [141]. Conversely, poor design may increase cognitive load and impair driving performance. In this regard, a recent study [167] showed that integrating machine learning and optimization algorithms into the design phase can help predict and minimize cognitive load, enhancing AR-HUD effectiveness for both driving performance and user comfort.

To ensure that GE designs remain effective across varying contexts and cognitive demands, several studies propose a user-centered approach and emphasize the creation of design guidelines and frameworks to improve a functional user experience (UX) and thus safety [10], [22], [26], [85], [109], [168]–[172]. Some approaches are oriented towards an iterative, AGILE-like design paradigm [10], [171]. Others focus on defining guidelines to follow when designing safe and efficient HUDs, such as focusing on visual ergonomics [149], or defining the positions and maximum number of GEs that should be displayed at any given time [22] and the type of information that should be accessible to the driver [85], [173].

Recently, a review of the existing literature on AR-HUD human-machine interfaces proposed a novel set of guidelines [26], with clear design recommendations on parameters such as the virtual image distance (optimal at 12–15 meters), FOV (greater than 10°), luminance (higher than 10,000 nits), prioritization of information and readability. At the same time, it clarifies how the displayed information should adapt to different driving contexts such as intersections, high-speed scenarios or traffic jams. Building on this perspective, the structured design framework presented in [44] aligns the visual elements with the cognitive and environmental demands of driving to reduce mental workload and improve hazard perception. This perspective reinforces the idea that an effective AR-HUD design should not only optimize the display parameters but also reflect the cognitive structure of the driving task itself.

Beyond design, further challenges arise in the evaluation of GEs. Many studies involve a limited number of participants (e.g., [7], [118], [120]), cover a narrow range of tasks (e.g., [162]) and interface designs (e.g., [134], [174]), and are restricted to short driving sessions (e.g., [94]). Therefore, despite numerous studies that have examined multiple GEs in different scenarios [29], [151] and even propose the use of biometric measurements to accurately assess mental workload [7], [80], it is still difficult to generalize their results, as some studies report inconsistent feedback between drivers with different demographic characteristics, experience and driving styles [82], [101], [151]. Then, much of this research is conducted using VR-based TEs, which provide a high level of experimental control but do not fully replicate the sensory, cognitive and situational complexity of real-world driving [13], [42], [162].

VII. PURPOSE

AR-HUDs can provide a wide range of information to assist the driver with various tasks that evolve as the vehicle's level of automation increases. As the driver's role shifts from full control to partial or full delegation, the function of HUDs also changes, providing targeted support based on the requirements of the driving context. To better understand how AR-HUDs contribute to task fulfillment and shape the overall driving experience across different automation stages, we introduce the concept of HUD *purposes*. In this context, a *purpose* refers to the specific *functional goal* that an AR-HUD is intended to achieve – such as supporting safety, navigation, or user trust – by facilitating the driver's performance of one or more underlying tasks. For example, the purpose of reaching a destination may involve maintaining lane position (*primary task*), following navigation instructions (*secondary task*), and answering a call to coordinate arrival time with a person at the destination (*tertiary task*).

Based on this analysis, we categorized the literature into five main purposes: *safety*, *wayfinding*, *non-driving-related tasks*, *take-over requests*, and *creating trust*. These purposes were derived inductively through a qualitative thematic analysis of the reviewed literature, in which recurring design goals were iteratively coded and grouped. Cross-validation among the authors ensured consistency in category definition. We

Fig. 9: AR-HUD interface for safety enhancement displaying icons with different colors depending on the distance, overlaid on every vehicle. Image adapted from [15].

highlight that, although analytically distinct, these purposes are not mutually exclusive, and partial overlaps may occur when the same AR-HUD feature serves more than one goal. For example, a Take-Over Request may simultaneously contribute to safety by preventing collisions and to user trust by reinforcing the reliability of automation.

A. Safety

Safety has been one of the key drivers for the development of HUDs, especially for the *active driver*, where the active involvement of the driver is still crucial and HUDs play a central role contributing to overall road safety, as demonstrated by several studies [16], [67], [83], [85], [175]. In this role, the driver must divide attention between monitoring the environment and interacting with vehicle interfaces, making AR-HUDs particularly effective, as they enhance situational awareness and reduce the cognitive demands traditionally imposed by Head-Down Displays [18], [81], [92]. However, as previously stated, inappropriate design or use can have a negative impact on driver performance, highlighting the need for careful consideration when implementing them [18], [22], [35], [70].

A substantial body of research has focused on how AR-HUDs can improve safety by supporting the execution of primary and secondary driving tasks. For example, various warning cues, such as forward collision alerts [40], [58], [75], [118], [142], [176], traffic information [2], [53], [57], pedestrian crossing warnings [14], [16], [35], [42], [60], [61], [81], [174], speed monitoring [62], [175], see-through functionalities [15], [56], and lane departure warnings [82], [124] have been proven to help reduce collisions with other vehicles and vulnerable road users; and are therefore invaluable in scenarios that require increased vigilance [14], [35], [57], [84].

Beyond safety-critical functions, HUDs can also reduce the time drivers take their eyes off the road during tertiary tasks [1], [84], [100], and improve situational awareness [70], largely reducing risk perception time and reaction time – e.g., respectively by 63% and 35%, as shown in [44] – even when non-safety-related GEs are displayed [66]. For example, displaying the vehicle speed directly in the driver's line of sight in combination with contextual visualizations such as a virtual carpet [6] or the estimated braking distance [62] can help avoid rear-end collisions.

Safety Challenges

Although many studies show HUDs effectiveness in improving road safety, not all results are entirely positive. In particular, certain design elements – such as excessive visual clutter or ambiguous GEs – might obscure important information, increase cognitive load and ultimately distract rather than enhance driver safety [18], [25]. A most striking example of this is the distinction between non-ARGEs and ARGEs. Since non-ARGEs are screen-fixed and lack spatial registration with the outside world, they can pull the driver's attention away from the road and have been shown to increase reaction times to hazards [162].

The effectiveness of AR-HUDs is also complicated by the variability of drivers' responses: what works well for one driver may not be suitable for another [70], [120], [134]. In addition, the perceived usefulness and effectiveness of ARGEs varies with the driving context. While they might improve spatial awareness in clear scenarios such as highway driving [77], they can become less intuitive in dense or cluttered urban environments where multiple visual stimuli compete for attention [35], [67], [85]. This heterogeneity underlines the importance of designing adaptive interfaces, which are discussed in Section VIII.

In line with the *driver-user continuum*, transitions in the HAR change the relevance of the safety support offered. For *active drivers* this support is critical, while for *passive users* these safety functions are delegated to the automated system, rendering safety assistance unnecessary.

B. Wayfinding

Wayfinding is essential to support *active drivers* reaching their destination. Traditional personal navigation devices might compromise safety by distracting the driver's attention from the road. AR-HUDs solve these problems by projecting navigation information directly into the driver's line of sight. This allows the driver to maintain eye contact with the road and focus on the driving task [54], [73].

A common non-ARGE designed to support wayfinding is *map-pathways* (Fig. 10, *Top*), in which a map of the surroundings is projected onto the windshield [54]. Although this helps keep the driver's eyes on the road, it does not significantly reduce route planning errors [91], [177]. Another approach, *turning instructions* (Fig. 10, *Center*), uses directional arrows projected onto the windshield to guide upcoming turns [42], [95]. Its simplicity makes it suitable for both full windshield and compact HUD systems [42].

On the contrary, ARGE-based solutions enhance the navigation experience by aligning wayfinding cues with the driver's natural line of sight, thereby improving both intuitiveness and safety. Among these, one of the most representative examples is the *virtual carpet* [7], [24], [67], [92], which projects a highlighted path onto the road surface ahead of the vehicle, displaying the route to follow in real time (Fig. 10, *bottom left*). This approach is particularly effective when implemented on full-windshield HUDs, as their extended field of view

Fig. 10: *Top*: map pathway, displaying a map where the route to follow is highlighted [92]. *Center*: turning instructions, set of chevrons pointing to the turning direction [90]. *Bottom*: virtual carpet, a continuous path indicating the direction to follow [72]. Images adapted from the respective studies.

allows seamless integration of route guidance without the perceptual constraints of smaller displays [71]. A complementary strategy is the use of *virtual zip-lines* [91], [177], which project an elevated trajectory above the driver's line of sight to visualize the upcoming route in advance, maintaining visibility even in the presence of other road users. This technique helps reduce route-planning errors and increases driver confidence by providing a clearer spatial representation of the intended path. *Direction indicators* are another ARGE that places arrows at intersections to signal turn points to drivers [7], [71], [72], [90] (Fig. 10, *Bottom, right*). These indicators become more prominent as the vehicle approaches a turn, facilitating smooth and timely navigation maneuvers, and they can also be combined with *virtual carpets* to create comprehensive navigation aids that improve the clarity of navigation instructions [7], [13], [67], [72].

Wayfinding Challenges

Although non-ARGEs offer simplicity and clarity, especially in situations where AR implementation is limited by display size, resolution or environmental factors [42], ARGEs offer improved turn anticipation, better speed control and greater driver confidence when navigating [13], [71]. However, their effectiveness depends on the driving scenario. Complex traffic conditions can hinder information processing and occasionally lead to distractions [7], underlining the need for AR guidance systems that adapt to the context.

Again, another major limitation in current research is the reliance on simulated environments when testing wayfinding solutions, which limits ability to accurately evaluate the effectiveness of different GEs in real-world driving conditions [13], [54], [92], [95].

C. Non-Driving Related Tasks (NDRTs)

These are tasks that do not directly support the *active driver* to the operation of the vehicle on the road. On the contrary, they often serve as distractions that can significantly impair the driver's situational awareness. NDRTs are typically categorized as tertiary tasks, such as operating the in-vehicle entertainment system [99], reading a document [102], and using a smartphone for messaging or social media browsing (Fig. 11), but they can also include some secondary tasks, such as entering a destination into a navigation device. In the context of in-vehicle human-machine interaction, NDRTs are tasks that have no direct relationship with the surrounding driving scenario. Therefore, ARGEs may offer little to no benefit in supporting NDRTs as witnessed by the fact that their use in this domain is virtually unexplored.

Nevertheless, NDRTs are still cognitively demanding tasks for the driver [104], especially at higher levels of driver's involvement where they compete with primary and secondary driving tasks. In these scenarios, non-ARGEs can help reduce distraction by keeping content in the driver's FOV, thus reducing gaze distraction [27], [103], [105] and reaction time [103], [114], [117]. Their integration with safety-related functions is particularly important. For example, when a driver is engaged in a phone call or performing an infotainment task, HUDs need to be coordinated with safety alerts to ensure timely reallocation of attention [88], [89], [117], [151]. This is where ARGEs can come back into play, i.e. not to support the NDRT itself, but to improve the driver's awareness of safety-critical events through spatially anchored warnings or visual redirection [117], [135].

As automation increases, the driver's involvement in primary and secondary tasks decreases. This not only changes when and how NDRTs are performed, but also requires new approaches to safety feedback and interface design that reflect evolving patterns of attention and engagement. However, current research on HUDs in these scenarios remains limited and often confined to conceptual frameworks or experimental setups that lack validation in real-world conditions [97], [145].

NDRT Challenges

A key open question is whether ARGEs are really necessary or beneficial for supporting NDRTs. The limited number of empirical studies in this area may not simply reflect a research gap, but rather a limited scope for ARGEs in this context [97], [129]. A second challenge concerns the evaluation of non-ARGEs to support NDRTs. Although such displays have

Fig. 11: Examples of GEs that support NDRTs on AVs. On the right of the HUD, we see several apps open (i.e., media player, video call app, and a social media comments section), while on the left a TOR request is displayed. Image adapted from [123].

shown promise in reducing distraction and improving reaction times, the evidence comes predominantly from VR simulations [13], [117], [135] and conceptual analyses [103] that do not fully reflect the complexity of real-world driving. Future research should therefore prioritize more ecologically valid approaches to clarify the practical benefits of HUDs, particularly with regard to ensuring seamless attention transitions between NDRTs and safety-critical events [100].

D. *Take-Over Request*

Take-Over Requests (TORs) are a defining feature of SAE Level 3 (Conditional Automation), where the automated system can handle driving tasks under certain conditions, but prompts the *fallback-ready user* to resume manual control when encountering scenarios that exceed its capabilities – such as unexpected obstacles, adverse road conditions or unclear traffic situations [27], [122]. During these critical transitions, HUDs and AR-HUDs effectively support users by keeping their visual attention on the road, improving situational awareness and reducing reaction time [107], [111], [124].

Since constant monitoring of the road is not required at this level of automation, users often engage in tertiary tasks such as making phone calls, texting or interacting with infotainment systems. An effective design of the HUD interface is therefore crucial to enable a smooth and safe transition from these NRDTs back to active driving [10], [19], [28].

Effective AR-HUD systems should be designed to assist *fallback-ready users* in the transition from a cognitively disengaged state during NDRTs back to active driving by providing clear, timely and spatially informative visual cues. In particular, ARGEs play a crucial role in immediately directing the user's attention to the cause of the TOR by providing intuitive, spatially relevant information [85], [103], [112]. While non-ARGEs have been shown to significantly reduce reaction times [105], ARGEs offer additional benefits by improving situational awareness and enabling smoother, less aggressive driving maneuvers [174], [178]. When AR is used to emphasize obstacles causing the TOR on the road, it contributes to increasing users' situational awareness, leading to earlier anticipation and smoother intervention [112] and might even provide assistance indicating the maneuver to perform, further reducing reaction time [178].

However, research that explicitly addresses the question of how AR-HUDs facilitate transitions between different attentional states and task types is still limited. Recent studies suggest that AR-HUDs that emphasize only essential elements of the road significantly improve situational awareness in different NDRTs [108]. On the other hand, studies focusing on NDRTs involving personal devices have found significant differences in how often and for how long users interrupt these tasks to observe the road [117]. Therefore, further research is needed to determine how AR-based interfaces can reliably support safe and effective re-engagement in different user behaviors and driving scenarios.

TOR Challenges

A key challenge in designing TOR interfaces is effectively managing the dynamic role of the *fallback-ready user*. Research has not yet explored how AR-HUDs could adaptively support this user through hybrid or graded modes that respond to different states of attention, driving contexts, and task complexities [151].

Another unexplored topic is how traffic complexity and situational constraints influence the perception and effectiveness of TOR cues. In dense traffic or complex scenarios, users may need more time to process spatial information and determine the appropriate response [105]. TOR interfaces must therefore not only present relevant data, but also put it into a clear context with the environment [112]. This task is well suited for ARGEs, although it has not yet been sufficiently tested under various real-world conditions.

Further challenges arise when hazards are not in the user's direct FOV, such as vehicles in the blind spot or obstacles in poor visibility conditions (e.g. fog, heavy rain). In these scenarios, conventional HUDs may be inadequate and AR-based cues need to be tested for their ability to visually redirect attention and compensate for limited perception [27].

However, visual cues alone are unable to re-engage a user whose attention is fully diverted from the road, as in the case they are engaged in NDRTs. In such cases, multimodal TOR alerts that combine HUDs with auditory or haptic feedback have been shown to improve user responsiveness [21], [115], [116], [119], [179]. These approaches increase the likelihood of critical warnings being recognized and become particularly effective when designed to reflect the urgency and context of the situation, offering graduated and intuitive support depending on the level of threat [107], [108], [121]. However, it is important that these feedback mechanisms prevent cognitive and visual overload by integrating TOR cues that minimize attentional conflict, while simultaneously adapting or suppressing ongoing NDRT content to ensure timely and safe user re-engagement [107].

E. *Creating Trust*

In automated vehicles, and especially for *passive users* that no longer engage in active driving tasks, trust in the system becomes a critical component for acceptance and user experience [129], [180]. Without traditional control or feedback mechanisms, passengers must rely entirely on the vehicle's actions and the information it provides. In this context, AR-HUDs offer a unique opportunity to foster trust by providing intuitive, real-time and contextual visual cues that make the vehicle's behavior more transparent and understandable [130].

This has led to a growing interest in integrating eXplainable AI (XAI) into in-vehicle Human-Machine Interfaces in automated driving to provide clear, understandable feedback on what the vehicle is doing, how it is perceiving its environment and why it is making certain decisions (e.g. [19]–[21], [127], [128], [131], [145]). AR-HUDs have emerged as promising tools for mediating this interaction. Studies show that *passive users* report less stress and higher acceptance of AVs when AR-HUDs comprehensively highlight elements in the driving environment (not just those relevant to the planned route) – even if this information might cause increased cognitive load [19] and motion sickness [20]. In addition, real-time visualization of vehicle actions and dynamic environmental factors significantly increases passenger confidence [128]. These results highlight the potential of AR-HUDs to improve XAI effectiveness, and consequently trust [181], by aligning with passengers' mental models and providing real-time explanations of vehicle behavior [145], opening up new opportunities for further exploration of design solutions that effectively support XAI through AR-HUDs [68], [128], [132].

Challenges in Designing for Trust and Explainability

Despite promising results, there are still some open challenges in using AR-HUDs to support trust and explainability.

First, to build trust, explanations must not only be clear, but also timely and relevant. Delayed or poorly contextualized cues can lead to confusion or even mistrust [20], [133]. Secondly, AR-HUDs should find a suitable compromise between the wealth of information displayed and the cognitive load of processing that information [20]. Then, trust is subjective and is influenced by previous experiences, familiarity and individual cognitive styles [128], [131], [133], which calls for XAI approaches capable of adapting explanations to users' mental models, preferences and familiarity [132] especially in the long term use, where learning effect plays and essential role [133].

VIII. SYSTEM ADAPTABILITY

Beyond being simple output devices, AR-HUDs function as adaptive mediators between the driver and the vehicle. Their effectiveness hinges on the ability to adapt along two main axes. The first, *driver-dependent adaptation*, involves tailoring the interface to internal, user-specific variables such as attention level, cognitive workload, personal preferences, or driving skill [28], [85], [134]. The second, *environment-dependent adaptation*, responds to external factors like traffic density, road geometry, or adverse weather and visibility conditions [53].

By dynamically adjusting both the displayed content and its modality based on this context, a well-designed system can enhance situational awareness, reduce information overload, and support safe and fluid interaction across different levels of automation. The adaptability of the visual output must also be complemented by *adaptive input mechanisms* to ensure seamless interaction along the entire driver–user continuum [29], [182]. Although adaptive AR-HUD systems are very promising, their successful design and deployment still face numerous challenges, which will be discussed in the remainder of this section.

A. Challenges: Driver Preferences and Adaptations

A key challenge in driver adaptation is balancing flexibility with cognitive simplicity [85]. AR-HUDs need to prioritize relevant information while avoiding clutter, especially when the driving context becomes complex or cognitively demanding. For example, interacting with the music controls via an AR-HUD can reduce distractions during normal driving, but can become an obstacle during critical maneuvers such as overtaking [28], [85], [183].

While the development of ecological interfaces (i.e., those based on the skills, rules and knowledge taxonomy of cognitive control [44]) seems to lead to more consistent results, effective adaptation also depends on the ability to tailor the HUD to the driver's individual characteristics. Factors such as age, driving experience and personal preferences have been proven to influence how information is processed and what level of visual support is most effective [54], [101], [134]. Thus, novice drivers may benefit from sustained and detailed guidance, while experienced drivers may prefer minimalist displays that do not interfere with their usual behavior [101], [134], [184].

Attention management is equally critical. While AR-HUDs are designed to keep essential information in the driver's FOV, there is a risk of an attention tunneling [185] where the driver fixates on the HUD and ignores important external stimuli [89].

B. Challenges: Road and Environmental Conditions

Adapting AR-HUD displays to different road and environmental conditions poses additional challenges. For example, in dense fog or heavy rain, it may be necessary for the AR-HUD to prioritize visibility-enhancing elements such as lane markings, vehicle proximity warnings or collision warnings [53]. In clear weather, however, these same elements may become redundant or even distracting [134]. Similarly, urban environments with high pedestrian activity and complex intersections may require different GEs than on open highways, where anticipation of long distances and speed control are more important [35], [85]. Adaptive systems should also have the capability to modulate the visibility, priority and persistence of visual elements based on driving conditions in real time, e.g., hiding secondary information during difficult maneuvers or highlighting TORs when urgent intervention is required [105].

To support this dynamic adaptation, AR-HUDs must integrate advanced sensors in real time that are able to monitor both external and internal factors, including driver alertness and fatigue, as well as sophisticated algorithms for real-time contextual data analysis and interpretation [89].

C. Challenges: Interaction Inputs Across Automation Levels

As the visual output of an AR-HUD must adapt to the driving context, the methods for user input must also evolve in response to the driver's changing role across the *driver-user continuum*. For *active drivers*, interaction should be fast and intuitive and rely on familiar input types such as tactile controls and simple voice commands [160], [182], [186], [187]. For *fallback-ready users*, input systems must support fast reengagement and avoid conflicts between NDRT interactions and critical alerts. In these situations, input modalities that can adapt to both urgency status and context (e.g. noisy cabins, low lighting) become essential [77], [107]. On the contrary, for *passive users* interaction becomes more diversified and comfort-oriented, requiring support for flexible and multimodal commands across a range of tasks [22], [135], [136], [151].

Despite the growing interest in gesture-, voice- and gaze-based input modalities [29], [106], [144], several challenges remain. One key issue is the ability of the system to accurately interpret the user's intent in dynamic contexts (for example, distinguishing between gaze used for control and natural observation [29], [188]) while remaining robust to ambient noise and distractions [189]. Another significant gap in current research concerns the interplay between interaction feedback and other vehicle signals. For example, it can be problematic to effectively convey vibrotactile feedback when the vehicle is driving on uneven terrain [190].

Moreover, the effectiveness of multimodal interactions remains controversial, with studies showing mixed results [88], [191]. Some recent studies have explored the potential of combining auditory and haptic cues with visual information to improve driver response and situational awareness in automated driving contexts [192], [193]. Although these works are not specific to AR-HUDs, they suggest that complementing the visual channel with non-visual feedback could reduce visual load and support faster, more reliable reactions across different human–automation roles. Defining effective strategies for integrating these modalities – such as timing coordination, latency management, and context-adaptive modality fusion – remains an open challenge for future AR-HUD research, particularly during transitions between *active driver*, *Fallback-ready*, and *Passive user* roles. This careful, context-aware design is especially crucial under the conditions of conditional automated driving, where multimodal systems must provide access to complex information without causing cognitive overload, particularly during safety-critical events such as TORs [22], [85].

IX. OPEN AREA OF RESEARCH

The review conducted in the previous sections has examined AR-HUD technologies across various purposes, driving contexts and human-automation roles. This section does not aim to provide new insights, but summarizes the main open questions and research gaps that we have identified. In particular, we focus on AR-HUDs evaluation, interaction techniques, contextual adaptability, and unified design frameworks. By defining these areas, we aim to highlight the key directions for future research needed to fully realize the potential of AR-HUD systems.

A. AR-HUD Testing

As discussed in Section V, effective testing of AR-HUDs requires more than isolated or fragmented assessments. It requires a structured, multi-stage evaluation framework – from early conceptual validation through to on-road testing – that captures the dynamic and contextual complexity of real-world driving. In parallel, to promote comparability and reproducibility between different studies, standardized test protocols need to be developed that define both the evaluation metrics and the test conditions. These protocols should include common metrics to assess cognitive load, usability, user experience and response time, as well as well-defined and repeatable scenario templates. In addition, these scenarios must take into account different driving contexts, including road types (urban, rural, highway), environmental conditions (weather, lighting) and traffic complexity. Finally, the samples of participants should reflect a wide range of driver demographics and experience to ensure robust and comprehensive design validation.

Our findings show that a considerable number of studies rely on VR to evaluate AR-HUD interfaces. Although VR is flexible, it often fails to accurately replicate the real-world technological constraints of AR-HUDs. In fact, many VR-based evaluations overlook critical limitations such as registration accuracy, latency, occlusion and brightness issues as observed in studies like [13], [25], [40], [62], [94]. Additionally, VR testing often neglects the effects of different road surfaces (e.g. paved or not) on sensor reliability and display stability, as well as the challenges posed by adverse weather conditions (rain, snow, fog) and complex lighting scenarios (glare, reflections). Ignoring these factors can lead to an overly optimistic assessment of system performance.

Traffic density and distractions in the cockpit (e.g. passengers, music, smartphone use) are other key variables that have been proven to influence the effectiveness of the HUD [2], [67], [101], [142], [194]–[196]. To reflect these realities, test design should also adopt a *situational fidelity* principle, accurately reproducing all driving tasks involved for each HAR.

B. AR-HUD's Adaptability

As discussed in Section VIII, an effective AR-HUD must adapt to both the driving context and the individual characteristics of the driver. However, current research often examines these aspects in isolation, without offering a unified or scalable approach to real-time adaptability.

In terms of the environment, future AR-HUDs should be designed to deal with dynamic variations in lighting, weather and traffic conditions through the use of advanced sensors and real-time data processing. While some progress has been made in simulating these conditions [55], systematic studies on adaptive behavior in different environmental contexts are still lacking. The use of advanced artificial intelligence approaches could enable systems to recognize environmental changes and adapt visual outputs accordingly [89].

Equally important is the dimension of *driver-centric adaptability*. Although individual variability in experience, cognitive load, and behavior is well documented [134], [141], most experimental setups involve homogeneous user groups and limited sample sizes. To develop truly personalized AR-HUDs, future research should prioritize the following aspects:

- real-time modeling of driver state (e.g. distraction, fatigue, workload);
- adaptive algorithms that modulate the AR-HUD content according to these states;
- testing on demographically and behaviorally diverse user groups [28], [101], [134].

Another often overlooked factor is the session duration. Most prototypes are tested in short driving trials, but longer driving sessions lead to fatigue and reduced attention [101]. These are conditions under which a static HUD can become ineffective or even distracting. Adaptive systems should be able to adjust the frequency, modality and relevance of information over time, taking into account the driver's long-term engagement and alertness.

C. AR-HUDs and Human Role Transitions

The introduction of the *driver–user continuum* highlights the variability in the design and evaluation of AR-HUDs across different HARs and the related user engagement. Sorting the selected studies along this continuum (Table III) reveals an uneven distribution.

While the current literature primarily explores AR-HUD support for primary and secondary driving tasks [31], their potential role in managing tertiary tasks and improving situational awareness during multitasking remains insufficiently investigated [151], as discussed in Section VIII. In particular, when supporting *fallback-ready users*, research is still limited on how AR-HUDs should seamlessly transition from general, non-ARGE content during NDRTs to urgent, driving-critical ARGEs during and after a TOR [122].

Then, as primary and secondary driving responsibilities are removed at SAE Levels 4–5, the benefits of AR-HUDs for the *passive user* become increasingly uncertain. Existing studies do not clarify whether ARGEs provide contributions in this role, for instance, by mitigating motion sickness [97] or enhancing trust through transparent vehicle explanations (XAI) [19]. Another unanswered question related to the *driver-user continuum* concerns multimodal interaction. As mentioned in Section VIII-C, input systems need to evolve to match the level of automation, the user's attention and the environmental context.

In conclusion, realizing the full potential of AR-HUDs across the entire driver–user continuum requires a unified design framework that takes into account different levels of automation and user engagement. As cognitive and perceptual requirements change with each level, AR-HUD systems need to adapt both the content displayed and the way users interact with it. The development of such adaptive, context-aware AR-HUDs will be crucial to ensure usability, safety and user trust in future autonomous vehicles.

D. Evaluation of AR-HUD Quality in Different Vehicles

While our research primarily concentrates on automotive technology as a whole, we observed that the majority of existing studies are focused on cars and only a small number of studies employ AR-HUDs on other land vehicles [197], [198]. This indicates a significant gap in the literature regarding the application and effectiveness of AR-HUDs in other types of vehicles, such as vans, fire trucks, police cars, garbage trucks, trucks, and semitrailers, which present unique challenges and opportunities for implementing AR-HUDs. For example, the height of the driver in relation to the road can affect the visibility and effectiveness of visual cues, while the position of the driver in relation to the windshield can also affect interaction with the system and its ergonomics. In addition, the intended use of the vehicle and the various tasks these vehicles perform can be greatly enhanced by AR-HUD support. For example, off-road vehicles could benefit from AR-HUDs that show hard to see obstacles or wheels contact points [199], which can help the driver move more effectively and safely over difficult terrain. Delivery trucks could use AR-HUDs to provide contextual information on wayfinding, traffic conditions, and delivery-related tasks not associated with driving [200], and industrial machinery such as excavators [197], [201], [202], heavy machinery [202], and forklifts [203] (which often operate in challenging environments where traditional Head-Down Displays are not as effective) could benefit from AR-HUDs that improve spatial awareness and operational safety. Furthermore, optimizing these interfaces for cognitive ergonomics is particularly relevant in such demanding contexts, where workload and attention management are critical for safety and performance [167].

E. Limitations of Current AR-HUD Research

The research gaps and open challenges identified above should be considered in light of several structural limitations that characterize the current AR-HUD literature. First, the available evidence is dominated by VR-based evaluations, which may limit ecological validity and the direct transferability of reported benefits to real-world driving. Second, research on higher automation contexts, especially those involving passive users at SAE Levels 4–5, remains comparatively sparse, so the corresponding insights should be interpreted as indicative rather than conclusive. Finally, the reviewed studies show substantial heterogeneity in experimental protocols, scenarios, and outcome measures (such as safety performance, glance behavior, workload, usability, and trust), often with non-uniform operationalizations and reporting practices. This variability hinders quantitative aggregation and motivates the qualitative, taxonomy-driven synthesis adopted in this work, which aims to provide a unifying perspective across driver roles and automation levels.

X. CONCLUSIONS

This paper provided a comprehensive review of automotive AR-HUD research proposing a structured taxonomy to organize existing studies by interface-related features and evolving human–automation roles. The analysis identifies consistent patterns across the driver–user continuum, showing that AR-HUD design goals, visualization strategies, and interaction requirements vary with the degree of human involvement in the driving task. Spatially registered AR elements are primarily used to support safety-critical and navigation-related functions during active driving, while higher levels of automation shift the focus to supervisory support, take-over facilitation, and user experience considerations. The review also highlights the growing importance of adaptability to both driving context and user state as a key design dimension across automation levels. By considering interface features, functional purposes, and human–automation roles together, the proposed taxonomy offers a coherent interpretative framework for structuring the fragmented literature and comparing existing approaches. The insights from this analysis, along with the identified challenges and open problems, provide direction for future research aimed at developing more effective, adaptive, and human-centered AR-HUD systems.

XI. ACKNOWLEDGEMENTS

This publication is part of the project PNRR-NGEU which has received funding from the MUR-DM352/2022.

Finanziato dall'Unione europea NextGenerationEU

Ministero dell'Università e della Ricerca

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

XII. DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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