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SURVEY

Human–Machine Interfaces: A Review for Autonomous Electric Vehicles

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ABSTRACT Human-Machine Interfaces (HMIs) play an important role in ensuring performance reliability to create safety and comfort during the operation of autonomous vehicles, by efficiently communicating their current state and driving intentions to drivers, passengers, and pedestrians. The motivation for this study emerges from the increasing development of autonomous vehicles and the critical need for effective HMIs to bridge the communication gap between these vehicles and their users. Examples of HMI technologies include visual displays for status updates, auditory alerts for immediate hazards, and haptic feedback for enhanced control. During automated driving tasks that may require users to take control of the vehicle under certain conditions, the interfaces must support the situational awareness of the drivers by providing effective communication of the situation. Design challenges include ensuring intuitive interaction, minimizing driver distraction, and achieving seamless integration with advanced vehicle control systems. The objective of this literature review is to present a comprehensive overview of the development of human-machine interface technologies in autonomous vehicles in different domain areas and to identify design challenges and opportunities to improve their interaction with their users.

INDEX TERMS Human-machine interface, autonomous vehicles, automated driving systems, performance reliability, situational awareness, user experience, vehicle-to-pedestrian communication, biometrics.

I. INTRODUCTION

Autonomous Vehicles (AVs) are a constantly evolving platform, their advances in technology have been implemented in commercial vehicles throughout the years. These advances range from the development of cruise control and anti-lock brakes to the introduction of advanced driver assistance features such as automatic emergency braking, which increases user safety while driving [1]. Autonomous vehicles are capable of performing automated driving tasks with the combination of sensors for environment perception, and navigation algorithms, but there are challenges in AV design regarding reliability to safety, comfort, and improving the situational awareness of the driver [2].

One important aspect of AV design is the development of effective Human-Machine Interfaces (HMIs) that provide a complete and intuitive interaction between the automated vehicle and its users [3]. Developments of HMIs in the automotive industry began with basic mechanical displays and simple infotainment systems. Innovations like CAN technology, Bluetooth connectivity, and touchscreens have led to the integration of advanced driver assistance systems and automated driving features, which have changed the focus of modern HMIs to enhance safety and user experience. HMIs in autonomous vehicles are essential to communicate the current state of the vehicle, and subsequent actions/intentions to drivers, passengers, and pedestrians, as well as being capable of receiving feedback from them to make decisions. Effective HMIs are critical for bridging the communication gap between the vehicle and its users, ensuring that drivers remain informed and can take control when necessary. Examples of HMI technologies include visual displays for presenting critical information, auditory alerts to warn of immediate hazards, and haptic feedback to provide physical

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sensations that enhance the driver's control and awareness. Current AV technology is only capable of operating at an automation level that requires the users to be alert of their surroundings while being prepared to take control of the vehicle under certain conditions, however, an ideal design of the HMI should be able to support the driver's situational awareness during non-driving related tasks (NDRTs) such as interacting with other passengers, using infotainment systems, using a personal device, among others [4]. The integration of advanced HMI technologies not only enhances safety by keeping drivers engaged and informed but also improves comfort and user experience by allowing seamless interaction with the vehicle's automated systems. Challenges in HMI design include creating interfaces that are intuitive and easy to use, minimizing driver distraction, and ensuring that the information provided is accurate and timely. These challenges are compounded by the need to design HMIs that can adapt to different levels of automation and varying user needs.

For this work, a systematic literature review of HMIs in autonomous vehicles is presented, where a structured process for search and selection of articles, as well as a synthesis and categorization of selected studies based on the systematic review protocol PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) [5]. The objective of this systematic approach is to provide a comprehensive overview of the current state and challenges of HMI technologies for the interaction with users of autonomous vehicles, including drivers, passengers, and pedestrians. Detailed information on the study selection criteria and processes is provided in the Methodology section. The selection criteria for the review are shown in Figure 1.

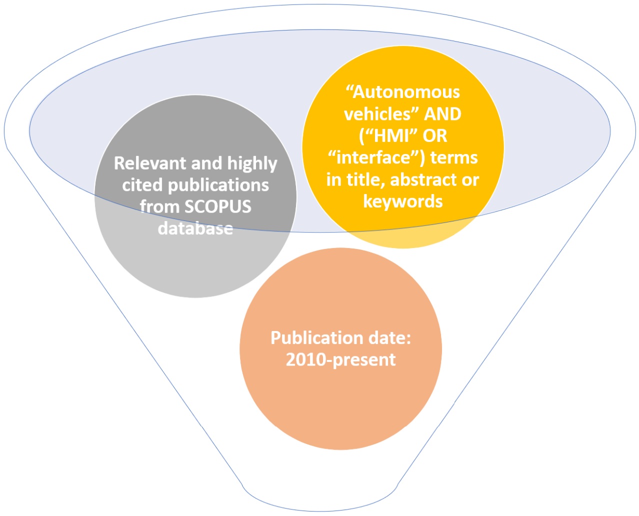


FIGURE 1. Selection criteria for publication analysis.

A. RESEARCH QUESTIONS

According to the objective of this review, the following research questions were posed:

- Research Question 1: What is the state of the art in HMI technologies in autonomous vehicle applications, and what are the implications of these technologies for future research and implementation?
- Research Question 2: What are the trends among researchers in the field of HMI design and the experimental platforms that are being used to evaluate these technologies?
- Research Question 3: What are the challenges researchers face when designing and testing HMI technologies, and how are they addressed to ensure their proposals provide useful information about their performance?

B. CONTRIBUTIONS

The main contributions that this review provides are:

- **A broad understanding of developments in Human-Machine Interface technology:** By analyzing the historical and current developments of HMI technologies, this review aims to offer a clear perspective of their evolution, and how this is supporting technology development in the field of autonomous vehicles.
- **An in-depth insight into emerging trends and novel technological developments in HMIs for AVs:** This review presents the latest developments in HMI technologies focused on AV applications, detailing common experimental platforms and performance indexes used for evaluating design concepts.
- **An evaluation of the challenges and limitations of HMI research strategies:** Finally, this work analyzes the challenges and limitations faced by researchers when developing and evaluating the performance of HMI technologies.

This review offers a comprehensive and up-to-date examination of HMI technology developments, including historical background, emerging trends, and evaluations of research strategies, with a particular emphasis on autonomous vehicle experimental platforms, applications, and performance assessment methodologies. In contrast to other reviews on the subject, such as [6], which focuses solely on external HMIs, and [7], which covers HMIs across different applications, this review categorizes HMIs based on the user interaction, whether by passengers inside the vehicle or pedestrians outside the vehicle.

This article is presented in the following structure. Section 2 provides a conceptual background on the key concepts and challenges regarding autonomous vehicles and HMIs. Section 3 describes the systematic approach that was carried out for this review, detailing the steps and search, the selection criteria, goals, classification, and literature complexity, while identifying a common architecture among authors regarding HMIs for autonomous vehicles. Section 4 presents the historical developments on HMIs, as well as the design and structure used for autonomous vehicle applications whereas Section 5 presents different aspects of HMIs for AVs detailing each experimental platform, commercial technology, trends, and challenges. A discussion of the observed challenges of current HMI developments is established in Section 6. Finally, the conclusions of the findings are presented in Section 7.

II. SCOPE AND CONCEPTUAL FRAMEWORK

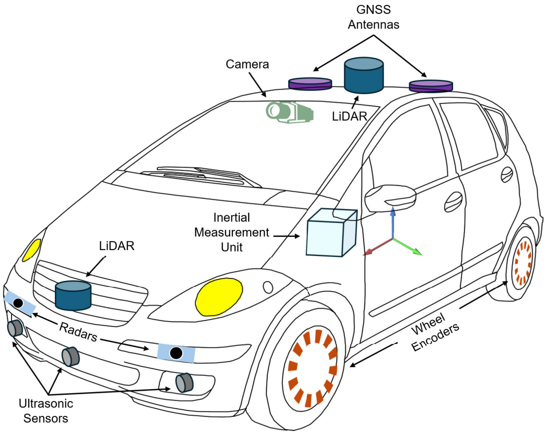
To provide context to the analysis, we begin by presenting the challenges that are present in electric AVs, which is the main research subject of the study. Then, additional relevant concepts are described such as the different autonomy levels that AVs can operate, the different vehicle classifications according to their size, the different architectures of HMIs in vehicles, and the use of biometrics of drivers, passengers, and pedestrians.

A. ELECTRIC AUTONOMOUS VEHICLE CHALLENGES

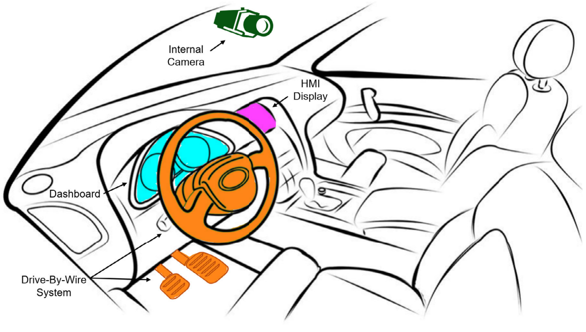
Electric autonomous vehicles have been regarded as the primary solution to many environmental and social issues in the automotive sector. These vehicles are equipped with multiple advanced technologies that allow them to recognize the environment they are operating in, and make decisions regarding the necessary action to ensure reliability for a proper driving experience. The most common sensors in AVs, as displayed in Figure 2 are as follows:

- **Light Detection and Ranging (LiDAR):** Provides high-resolution 3D mapping of the vehicle's surroundings, aiding in object detection, localization, and navigation [8].
- **Cameras:** Used for visual perception, object detection, traffic signage recognition, lane detection, and pedestrian detection [9].
- **Radar:** Offers long-range detection capabilities, especially in adverse weather conditions, for detecting vehicles, pedestrians, and obstacles [10].
- **Ultrasonic Sensors:** Assist in close-range object detection, particularly useful for parking assistance and maneuvering in tight spaces [11].
- **Global Positioning System (GPS):** Provides precise localization data, essential for navigation and route planning [12].
- **Inertial Measurement Unit (IMU):** Measures vehicle motion and orientation, aiding in localization, navigation, and stabilization [13].
- **Environmental:** Including temperature, humidity, and barometric pressure sensors, to gather data about the vehicle's surroundings for enhanced situational awareness [14].

The common AV system architecture, as displayed in Figure 4, consists of a perception layer that acquires environmental information through the use of sensors and the fusion and processing of collected data; such data is then analyzed and interpreted by a decision layer which generates planning information; the planning information is sent to an action layer that takes control of the vehicle according to commands from the decision layer. Recent advancements have focused on improving the decision-making and control processes within this architecture. For example, neural network-based model reference adaptive control (MRAC), have been explored to enhance the robustness and accuracy of the decision-making process in dynamic environments [15]. Additionally, model predictive control techniques can be applied to optimize the performance of electric motors and other critical components in real-time, ensuring efficient and reliable operation [16]. Furthermore, robust control methods, such as Particle Swarm Optimization (PSO) tuned controllers, have been developed for UAVs to stabilize altitude and track trajectories effectively, showcasing the potential for application in AVs to improve navigation and stability [17]. Although HMIs in AVs don't provide explicit information about control strategies, they focus on conveying insights into the environmental model and action strategies. One application of these technologies in a commercial AV setting can be seen with Waymo One$^{\text{TM}}$ ride-hailing service which utilizes an HMI design shown in Figure 3 that displays the vehicle's current route, LiDAR detection of nearby vehicles, and traffic light statuses at intersections which ensures clear communication with the user and can be personalized to their preferences such as language, enhancing safety by providing transparent, real-time insights into the autonomous vehicle's perception and decision-making processes.



(a) Autonomous vehicle external view



(b) Autonomous vehicle internal view

FIGURE 2. Schematic of common sensors and actuators in an autonomous vehicle (a) exterior view, (b) interior view.

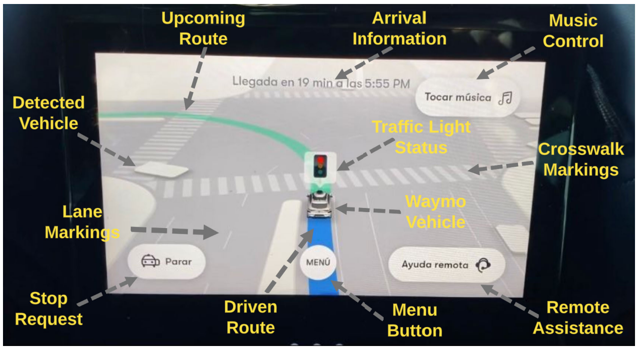


FIGURE 3. **Waymo One$^{\text{TM}}$ HMI example with environmental model elements.**

There are still important political, ethical, safety, and legal issues that limit the deployment and reliability of autonomous vehicles [19]. Reliability assessment of AV systems is in high demand before they are launched on the market, the concept of reliability must be expanded to consider more safety-related issues [20]. One way to address reliability is through HMI design; elements of each layer of the AV need to work in coordination to minimize errors that could negatively impact the driving experience and the information of these elements can be presented through the use of HMIs so that the AV users can be informed about the vehicle status, and be alerted if there are conditions that require them to take control of the vehicle. For instance, genetic algorithm-tuned controllers have shown promise in optimizing control systems to handle uncertainties and improve overall performance reliability [21]. Additionally, solving optimal path planning problems using advanced techniques like the Bidirectional Rapidly-exploring Random Tree Star (BRRT*) combined with the Dynamic Window Approach (DWA) and Adaptive Monte Carlo Localization (AMCL) has been crucial for ensuring precise and reliable navigation in dynamic environments [22]. The challenges of HMI design involve improving users' perceived safety, reliability, and experience to increase the acceptance of autonomous vehicles [18]. Additionally, because the high complexity and dimensionality of driving behavior, the efficient evaluation of the multidimensional performance of autonomous vehicles in simulation and real-world scenarios is a long-established problem [23].

B. AUTOMATION LEVELS AND VEHICLE CLASSIFICATION BY SIZE

The automated driving characteristics of a vehicle are commonly defined in function to the required human intervention needed to operate. The Society of Automotive Engineers (SAE) has proposed six different levels of automation, separated into driver support features for the first three levels and automated driving features for the remaining levels [24]. In addition to the SAE levels of automation, vehicle classification by size is another relevant concept for automotive performance assessments. According to different national automotive groups and associations such as the National Highway Traffic Safety Administration (NHSTA) and the Automotive Science Group (ASG), vehicles can be classified by their size, separating into different classes in accordance to parameters such as curb weight, interior volume index, and gross vehicle weight rating [25], [26].

C. HUMAN–MACHINE INTERFACES IN VEHICLES

Automotive Human-Machine Interface (HMI) refers to the interface between human and machine control systems, including software, hardware, interfaces such as dashboard displays, infotainment systems, touch screens, voice recognition systems, and other control mechanisms used to interact with the vehicle's onboard systems and functions. In autonomous vehicles, the HMI includes interfaces designed to facilitate user interaction related to control with the vehicle's autonomous driving functions, such as setting navigation destinations, monitoring system status, and overriding automated controls when necessary. HMI functionalities differ depending on the automation level of the vehicle they are implemented. Lower levels may only focus on displaying the current state of the vehicle characteristics to the user, while higher levels should inform additional information regarding the driving mode of the vehicle, environmental information, and even motion and maneuver intentions to provide awareness of the surroundings [27].

D. BIOMETRICS OF DRIVERS, PASSENGERS AND PEDESTRIANS

Biometrics consists of the capturing of relevant physiological data and behavioral characteristics through sensor technology. These characteristics are commonly used for the development of HMI systems that can evaluate a driver's condition during driving tasks, such as drowsiness and vigilance alertness, via face-monitoring systems that measure changes in eye regions and particular head rotations that may indicate that the driver is distracted or fatigued [28]. Other biometric parameters that can be used to enhance HMI functionality include Blood Pressure-Volume (BVP), Galvanic Skin Response (GSR), Heart-Rate Variability (HRV), respiratory frequency, and hand trembling, among others. The general flow process of a biometric system, as presented in Figure 5, consists of an initial registration process, where biometric data is captured from individuals through a sensor unit; a feature extraction unit processes the sensed data to extract relevant information and store it in a local database unit. Next, in a separate recognition process, a biometric input is captured by the same sensor unit, where the feature extraction unit processes the data to extract the target characteristics, and then, through a matcher unit, the extracted features are compared with those from the database unit to feed the decision algorithm of the application they are implemented in [7].

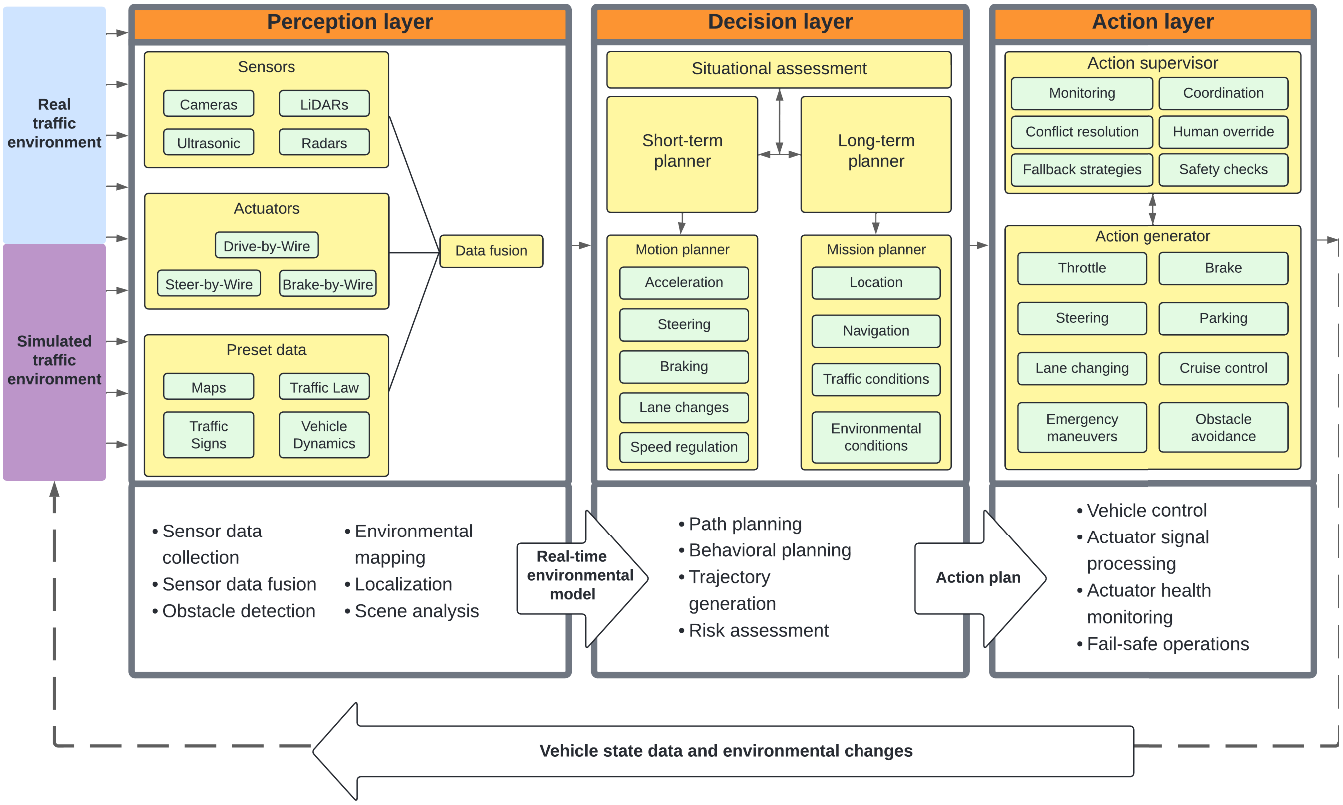


FIGURE 4. **Architecture of an autonomous vehicle, image modified from Wang et al [18].**

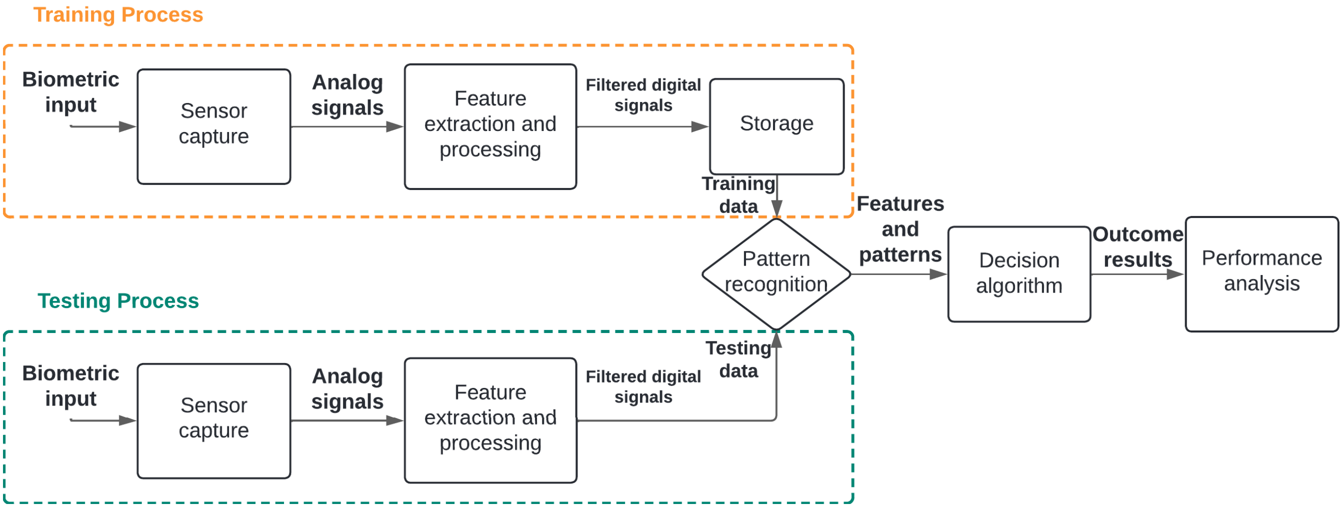


FIGURE 5. **Process flow of a biometric system.**

III. METHODOLOGY

This section details the process that was carried out to conduct the systematic literature review. The gathered literature was selected based on specific search methods and criteria that ensured an updated state-of-the-art revision of HMI technologies in autonomous vehicles. The review followed the systematic review protocol PRISMA to ensure transparency and reproducibility. Six stages have been considered in this systematic literature review, briefly described in the next paragraphs.

A. STEPS AND SEARCH

In the identification stage, a comprehensive search of various types of publications including journal articles, conferences, and reviews, among others, was conducted using SCOPUS as the main research database. Specific keywords including "autonomous vehicles", "self-driving vehicles", "human-machine interfaces", and "HMI", were used to ensure the study's themes were related to the research topic.

B. SELECTION

Following identification, the screening process involved reviewing the titles and abstracts to exclude duplicates and irrelevant studies. The screening process ensured that the remaining studies met the inclusion criteria by focusing on their relevance to the topic and their contribution to understanding HMI technologies in autonomous vehicles.

For determining eligibility, an assessment of the full texts of the screened articles was conducted. The criteria for eligibility included relevance to the development and application of HMI technologies in autonomous vehicles, a focus on interaction with users (including drivers, passengers, and pedestrians), studies published between 2010 and the present to ensure the inclusion of recent advancements and trends, and the inclusion of empirical data, experimental methods, or comprehensive reviews related to HMIs in autonomous vehicles.

Once the set of keywords and the research database were defined for the search process, the following selection criteria was established, as Figure 1 illustrates:

- Year of publication: 2010 to present.
- Publications with the terms "autonomous vehicles" (or similar), "HMI", "interfaces" in their keywords or title.
- Selection priority to publications by number of citations in SCOPUS database search.
- Publications whose HMI study subject presented a SAE Level of automation between 2 and 4.

Studies with descriptive elements of HMIs in the automotive sector with an emphasis on autonomous vehicles were the main objective of the selection process.

This structured process ensured that the review was comprehensive and included high-quality studies that provide valuable insights into the state and challenges of HMI technologies in autonomous vehicles.

C. ARCHITECTURE OF HMIs IN AUTONOMOUS VEHICLES

The selected papers were classified according to the HMI architecture used in cars, specifically focusing on internal and external interfaces.

The general architecture of HMIs in autonomous vehicles consists of an input channel and an output channel. The input channel can perceive inputs not solely from the drivers but also from passengers and external factors such as pedestrians, weather and road conditions, and other vehicles through the use of sensors, which can include visual technology, biometrics, etc. The output channel consists of extracting features from the input channel and communicating them internally to the users of the automated vehicle and externally to pedestrians. To better understand the specific roles and design challenges of HMIs, it is useful to distinguish them between internal and external interfaces.

Internal interfaces focus on the interaction between the vehicle and its users, primarily the driver and passengers. These interfaces are responsible for providing information about the vehicle's status, upcoming maneuvers, and situational awareness. Effective internal HMIs ensure that drivers remain informed and engaged, reducing the risk of accidents and improving overall safety. They also enhance the user experience by integrating infotainment systems, navigation aids, and personalized settings.

External interfaces, on the other hand, are designed to communicate the vehicle's intentions to external entities such as pedestrians. These interfaces play a crucial role in ensuring the safety of vulnerable road users by providing clear and intuitive signals about the vehicle's actions, such as stopping, turning, or yielding. External HMIs often use visual displays, lights, and sounds to communicate messages effectively. The distinction between internal and external interfaces in autonomous vehicles is critical because it highlights the different user groups and interaction contexts that each type of interface must address.

This architecture framework was chosen because it provides a comprehensive approach to understanding the multiple interactions that are present in autonomous vehicles. By categorizing HMIs into internal and external interfaces, we can more effectively analyze and address the specific design challenges and opportunities associated with each type. This classification aligns with the main goals of this review, which are to present a comprehensive overview of HMI technologies, identify design challenges, and explore opportunities to improve user interaction with autonomous vehicles.

Figure 6 presents an architecture of the external and internal interactions performed in autonomous vehicles based on [27] to illustrate the feedback loops between the vehicle and its various user groups.

For internal interactions, the HMI input from the driver and passengers to the AV includes functions such as navigation, driving mode selection, communication, control override, customization settings, and comfort controls. These inputs help in guiding the AV's actions and ensuring that the vehicle operates according to the user's preferences and needs. On the other hand, the HMI feedback from the AV to the driver and passengers includes critical information about vehicle condition, environmental conditions, system alerts, automation status, motion intentions, and energy consumption. This feedback loop ensures that users are kept informed about the vehicle's status and can make informed decisions or take control when necessary.

For external interactions, the architecture encompasses interactions with the external environment, pedestrians, and road users. The AV receives environmental data such as road type, traffic rules, weather conditions, and infrastructure information, which are crucial for safe navigation and compliance with traffic laws. In interactions with pedestrians, the AV detects pedestrian presence and location, gestures, and crossing intentions through sensors. It communicates

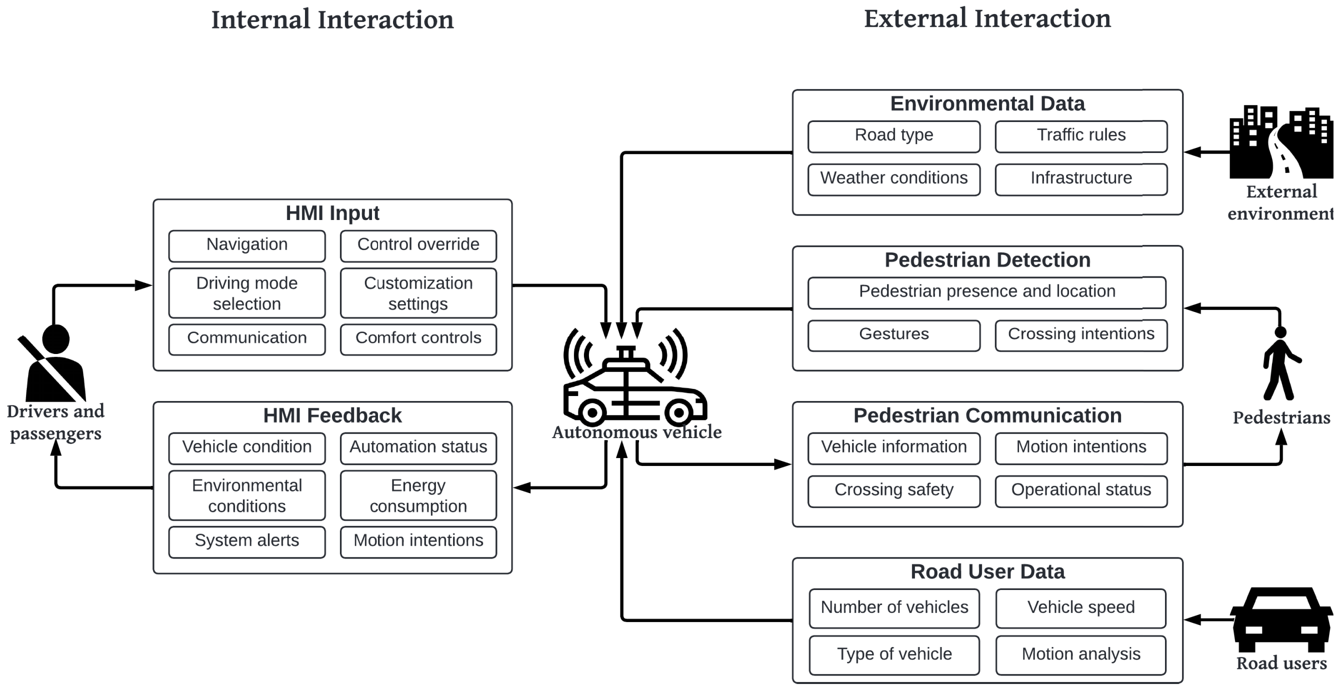


FIGURE 6. General architecture of interactions in autonomous vehicles.

back to pedestrians with information about the vehicle's current status, motion intentions, and operational status, enhancing pedestrian safety and confidence in interacting with autonomous vehicles. For road users, the AV gathers data on the number of vehicles, their speed, types, and performs motion analysis to navigate effectively and safely in traffic.

D. GOALS

The goal of this literature review is to present trends in the development of HMI technologies in autonomous vehicles in different areas of the previously stated architecture, and the challenges it entails.

E. CLASSIFICATION

The selected studies were sub-categorized in accordance to the following topics:

1) History of HMIs in autonomous vehicles.
2) Designs and experimental developments in HMIs for autonomous vehicles.
3) Biometrics in autonomous vehicles' HMIs.
4) Specific application of autonomous vehicles and their HMIs.

F. COMPLEXITY

The complexity of each topic is intended to present the main contributors to the development of the different HMI technologies in autonomous vehicles, as well as expanding into existing standards and regulations, and describing trends and challenges.

IV. LITERATURE REVIEW ON HMIs: HISTORICAL DEVELOPMENTS, DESIGN AND STRUCTURE FOR AUTONOMOUS VEHICLES

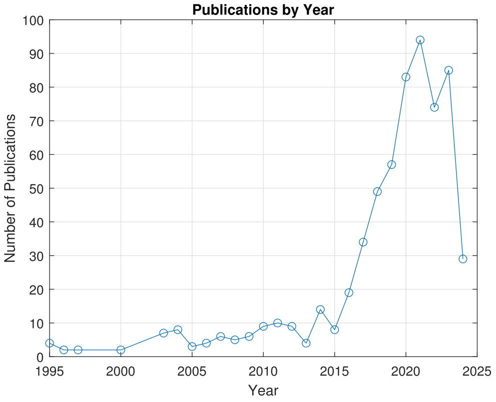
In recent years, research in the field of HMIs in autonomous vehicles has seen quick growth. Analyzing the scientometric information of the literature review, as shown in Figure 7, using the keywords combination "autonomous vehicles" AND "human-machine interface" AND "systems", it is shown that research in this topic began to gain momentum around 2010, and it exponentially grew from 2016 onward, and it has continued to increase, demonstrating that the field has a lot of potential and research opportunities. The main contributors to research on the topic are Germany, the United Kingdom, and the United States, with each country making significant contributions. Other countries, such as China, Italy, and Japan, among others, have also shown developments in the area. Most of the research in the field of HMIs in autonomous vehicles has been published in the form of articles and conference papers, with some book chapters and reviews also available. The main subject areas involved in the research are engineering, computer science, social science, and mathematics.

In this section, we begin detailing the historical developments of HMI technologies in the automotive sector. Next, different uses of HMIs in autonomous vehicles will be presented, including standards and regulations, and expanding on the common approach that is being used for the development of internal and external human-machine interfaces.

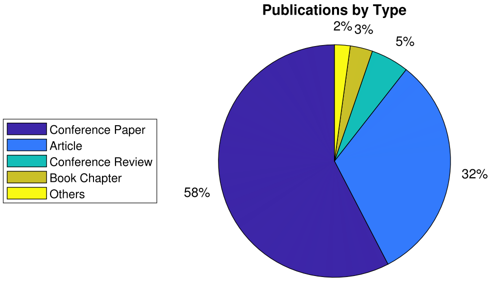
A. HISTORY OF HMIs IN VEHICLES

Most of the current research in the field of HMIs in autonomous vehicles focuses on the development of interfaces that enhance performance reliability to improve the safety and experience of the users. However, it is important to analyze the historic developments of interfaces in the automotive industry since they reflect the changes in preferences and expectations of drivers and passengers that have impacted their design and evaluation methods.

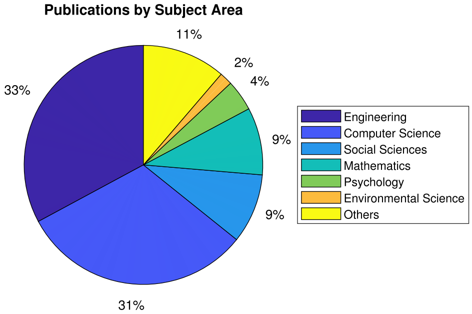
Figure 8 shows a timeline of interface developments in vehicles. Meixner et al. [29] provide an insight into the evolution of HMIs in the automotive sector. HMI developments started with purely mechanical displays in 1915. Manufacturers moved displays to less distracting locations and introduced entertainment features like car radios, in-vehicle phones, and cassette and CD players. Bosch introduced CAN technology in 1986, allowing communication between devices and the development of infotainment systems that, like Mercedes-Benz CNS in 1993, led to models and guidelines being introduced regarding safe HMI design. By this time, developments in Advanced Driver Assistance systems (ADAS) began to emerge. In the 1980s, driver assistance systems used proprioceptive sensors that measured the status of the vehicle and allowed controlling the vehicle dynamics, which then evolved to the use of exteroceptive sensors which measured external conditions of the vehicle to provide information and warnings [30]. Technological innovations like Bluetooth and internet connectivity were implemented in the 2000s, along with resistive touchpads. Additional developments in automotive HMIs involve the transition from resistive to capacitive touchpads for improved response, and the introduction of combiner and windshield displays that decreased eyestrain and presented driving information in the driver's field of view [31]. Finally, in the 2010s, further developments for driver assistance systems that provided automated driving features were accomplished.



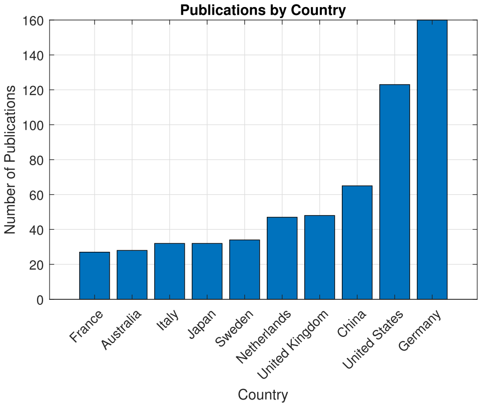
(a) Number of publications by year



(b) Percentage of publications by type



(c) Percentage of publications by subject area



(d) Number of publications by country

FIGURE 7. Scientometrics of SCOPUS search by (a) year, (b) type of publication, (c) subject area, and (d) country.

B. HUMAN–MACHINE INTERFACE DESIGN IN AUTONOMOUS VEHICLES

A common approach for the design of HMIs in autonomous vehicles relates to the emphasis on ensuring the safety of the user through the use of different stimuli such as visual, auditory, and haptic that assist and encourage the interaction with the interface [32]. Additionally, it is important to make a distinction between interfaces that interact with both drivers and passengers, which are commonly referred to as "internal HMIs" (iHMI), and vehicle interfaces that communicate with pedestrians denoted as "external HMIs" (eHMI). In both cases, HMI design should be user-centered, which involves providing transparency about the autonomous system by presenting information in a simple, but understandable manner to avoid overloading the users with non-relevant information that could negatively impact

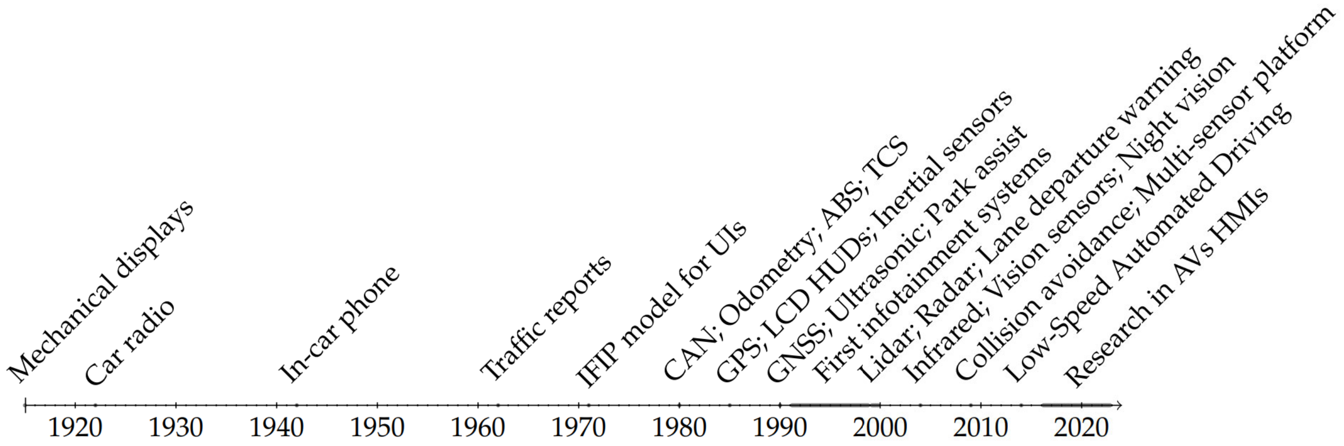


FIGURE 8. **Timeline of developments of HMIs.**

their decision-making under manual and autonomous driving circumstances, which would also decrease the system's reliability and affect the acceptance of automated vehicles [33]. Figure 9 shows the distinction between the different types of human-machine interfaces in autonomous vehicles, detailing the technologies, simulation, and experimental platforms and type of information that have been documented.

1) INTERNAL HMIs IN AUTONOMOUS VEHICLES

Internal HMIs of autonomous vehicles focus on providing information about the vehicle and its surroundings to both drivers and passengers. Research regarding this topic has been primarily focused on the elements and characteristics of the interface that improve safety, comfort, user experience, and acceptance of autonomous vehicles. One of the most important aspects of HMI design for safety is improving the situational awareness of drivers in an environment where autonomous driving is being performed while drivers perform non-driving related tasks [45]. An example of the HMI elements that can improve this situational awareness is the implementation of displays that present information about the status of the vehicle between the drivers and passengers in a design concept that allows the driver to perform other activities that also improve their comfort [46]. Another factor that can contribute to improving the situational awareness of a driver who is not performing driving activities is the addition of auditory stimulus that decreases the visual workload required to monitor the vehicle information through the use of only visual displays [47].

Multiple studies have corroborated that one common performance index that can be tested to indicate safety in HMI design is the take-over time, which involves the time drivers take from when the HMI in the vehicle indicates to them that manual driving is required, to when they regain control of the vehicle [48]. Other alternative actions to increase the situational awareness of users via HMI design can be through the use of different stimuli such as visual, auditory, and vibrotactile signals that can impact the drivers' responses, with a combination of these, take-over processes can be done more quickly to avoid any negative impact on the driver's manual driving behavior [49], which is essential for ensuring performance reliability and experience in an automated vehicle.

Other aspects that have been studied are related to how the HMI elements must be presented to improve the users' understanding of the system alerts and information on driving conditions. Figure 10 shows an example of an internal HMI concept that communicates many aspects of an autonomous vehicle. Elements such as color coding and the use of standardized and recognizable signs for announcing relevant events can improve how drivers interpret the messages of HMIs in autonomous vehicles [50], [51]. The use of augmented reality (AR) can be implemented in conjunction with the visual technologies implemented in the perception layer of the autonomous vehicles to display information about the road, environmental conditions, and infrastructure, among others, HMI design can take advantage of this by indicating the users the identified road and using graphic elements such as carpet and arrows over the displayed road to indicate maneuver intentions of the autonomous vehicle such as lane changes, braking, speed regulation based on road signals, etc [52], [53].

2) EXTERNAL HMIs IN AUTONOMOUS VEHICLES

External HMIs' primary function relies on transmitting the current vehicle's state and its intent information for short future to the rest of the traffic participants [6]. Figure 11 shows the interaction between vehicles and pedestrians using vehicle sensors to capture human features and display them through vehicle actuators for communication. The topic of research for external HMIs focuses on the development of improving communications using V2X devices between the autonomous vehicle and traffic participants such as traffic signage infrastructure, pedestrians and other vehicles driven by humans with a specific focus on the interaction with

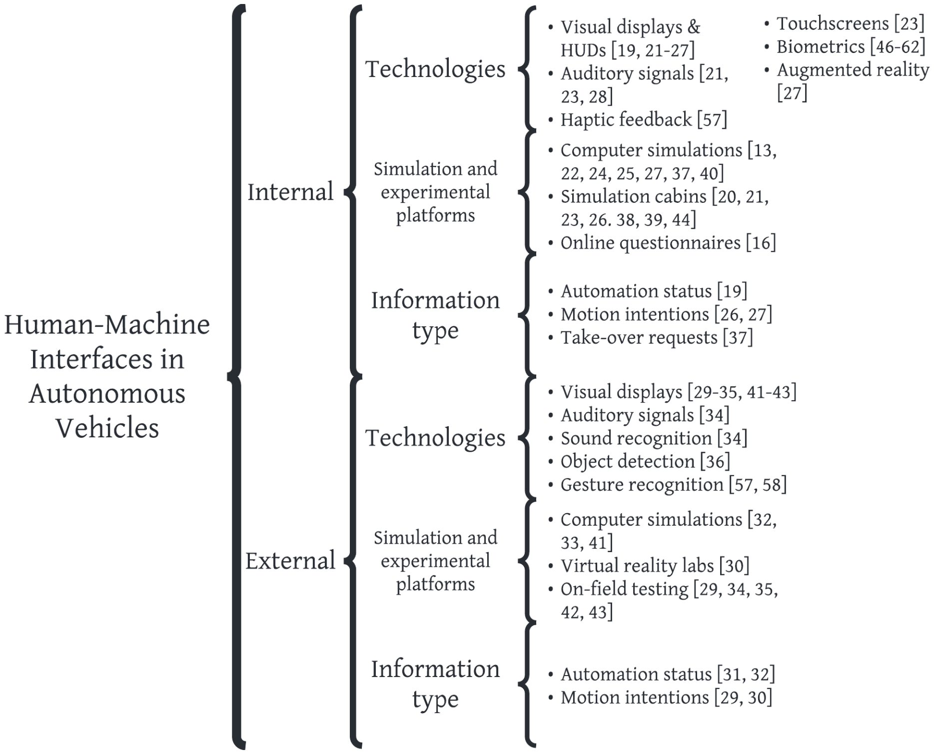


FIGURE 9. Human-machine interfaces in AVs.

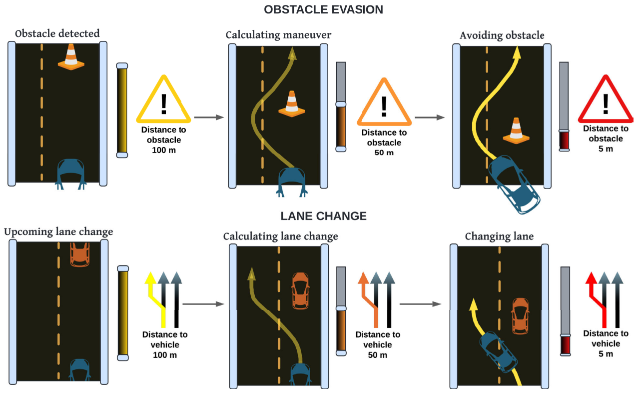


FIGURE 10. Internal visual HMI design concept for communicating vehicle status, motion intention and maneuvers.

pedestrians since they are the most vulnerable group in human-machine interactions.

In conventional vehicles, the use of lights and headlights makes communication possible in everyday interactions and situations including challenging environments where reduced visibility is present. In autonomous vehicles, external HMIs are used to accelerate pedestrians' inferences about their motion intentions [54], [55]. The visual design of autonomous vehicles is an aspect that makes them stand out from commercial cars. Perception technologies such as LiDARs and cameras may indicate to pedestrians that a different type of vehicle is in front of them, so additional visual elements are needed to indicate driving conditions and intentions, such as visual displays in combination with LED strips that communicate with pedestrians via text and symbols as demonstrated in Figure 12. The use of these elements can improve decision-making in crossing situations and increase the safety perception of pedestrians [56], [57]. In external HMI design, there are certain characteristics for the implementation of the previously described visual elements such as color, positioning, and contents that can affect communication with pedestrians. External HMIs positioned on the roof of the autonomous vehicle that transmit messages to pedestrians in crosswalking situations indicating actions that they are allowed to perform safely like "walk", have had a higher preference for perceived safety over preventive warning messages that explicitly state actions that pedestrians should not do like "don't walk" [58].

An additional characteristic of human-machine interactions relies on the use of auditory stimuli for communication. Sound as a method of communication is something relatable to pedestrians since conventional vehicles use speakers to indicate warnings and engine sounds to indicate their presence. For autonomous vehicles, their electric nature makes their engines produce different sounds with typically lower intensities, so alerting sounds and soft warnings are methods by which they can communicate with pedestrians without the need to look at the vehicle, such as the use of artificial sound generators, in combination with visual elements, can increase performance reliability and safety [60]. Pedestrians may also

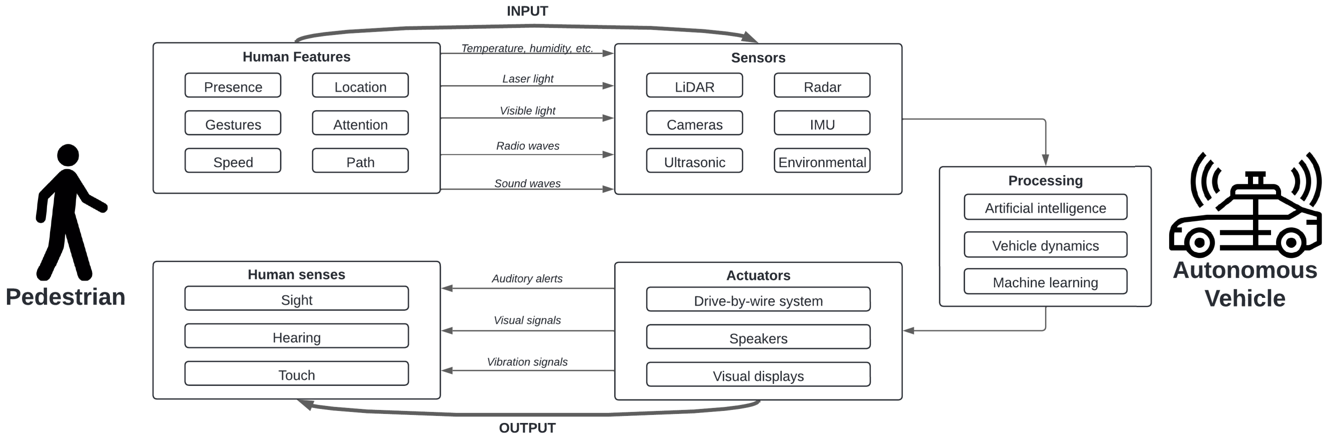


FIGURE 11. eHMI interaction scheme.

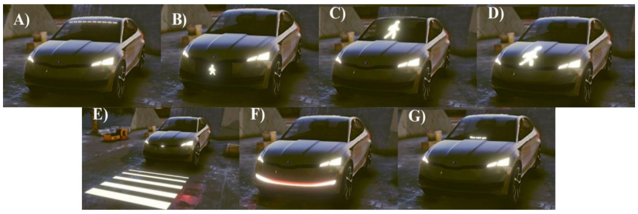


FIGURE 12. External HMI visual elements proposals: a) LED Bar, b) Bumper Panel, c) Windshield, d) Hood, e) Road Projections, f) Vehicle Mask, g) Interior Panel, image modified from Orlický et al. [59].

prefer that the messages be displayed visually in the external HMI, and AVs should also be communicated through audio due to environmental conditions that could affect its visibility such as direct sunlight or foggy conditions, or physiological limitations such as visual impairments [61].

A seemingly overlooked aspect in external HMIs is related to the cultural factors that can affect the effectiveness of their design. Certain characteristics of the external HMI such as symbols, and colors may convey different messages depending on the country, and pedestrian behavior, cultural norms, and expectations about technology and automation could impact their reactions to automated vehicles [62]. To this extent, cultural adjustments need to be considered upon the decision to implement this type of technology.

C. STANDARDS AND REGULATIONS FOR AUTONOMOUS VEHICLES HMIs

Currently, as far as the authors have researched, there are no official standards that focus on guidelines for the design of both types of HMIs in autonomous vehicles. The NHTSA in the United States does not have specific performance reliability requirements to design for HMI systems in autonomous vehicles. However, NHTSA's regulations and guidelines aim to ensure the overall safety and effectiveness of vehicle operation, including aspects related to HMI performance. Specifically, NHTSA's Federal Motor Vehicle Safety Standards (FMVSS) cover various aspects of vehicle design, construction, and performance, which indirectly influence HMI reliability. For example, FMVSS 101 specifies requirements for controls and displays, including factors such as visibility, readability, and ease of use, which are critical for HMI performance [34]; while FMVSS 135 addresses brake systems, including warning light indicators [35]. FMVSS 126 addresses electronic stability control (ESC) systems, including HMI interfaces, to enhance vehicle stability and prevent rollover accidents, and others [36]. While NHTSA has not issued specific reliability requirements for HMI in autonomous vehicles, automakers, and technology developers typically adhere to industry best practices and standards to ensure the reliability, usability, and safety of HMI systems. This may involve rigorous testing, validation, and human factors engineering to address potential failure modes, usability issues, and safety concerns related to HMI design and functionality. Additionally, companies often conduct user studies and gather feedback to iteratively improve HMI reliability and user experience over time.

Other existing standards related to HMI design in autonomous vehicles come from the International Organization for Standardization (ISO). For instance, ISO 26262 specifies functional safety requirements for automotive systems, including HMI components, to mitigate risks associated with malfunctions and failures [37]. ISO 15005 focuses on the ergonomics of human-system interaction in vehicles, addressing HMI design principles, display legibility, and user interface considerations [38]. ISO 9241 covers human-centered design principles for interactive systems, including HMI interfaces, emphasizing usability, accessibility, and user experience [39].

On the other hand, the SAE has proposed the following standards: SAE J3016 defines levels of driving automation and terminology for autonomous vehicle systems, including HMI functionalities [24], and SAE J2395 specifies guidelines for vehicle user interfaces to ensure safe and intuitive interaction with automated driving systems [40].

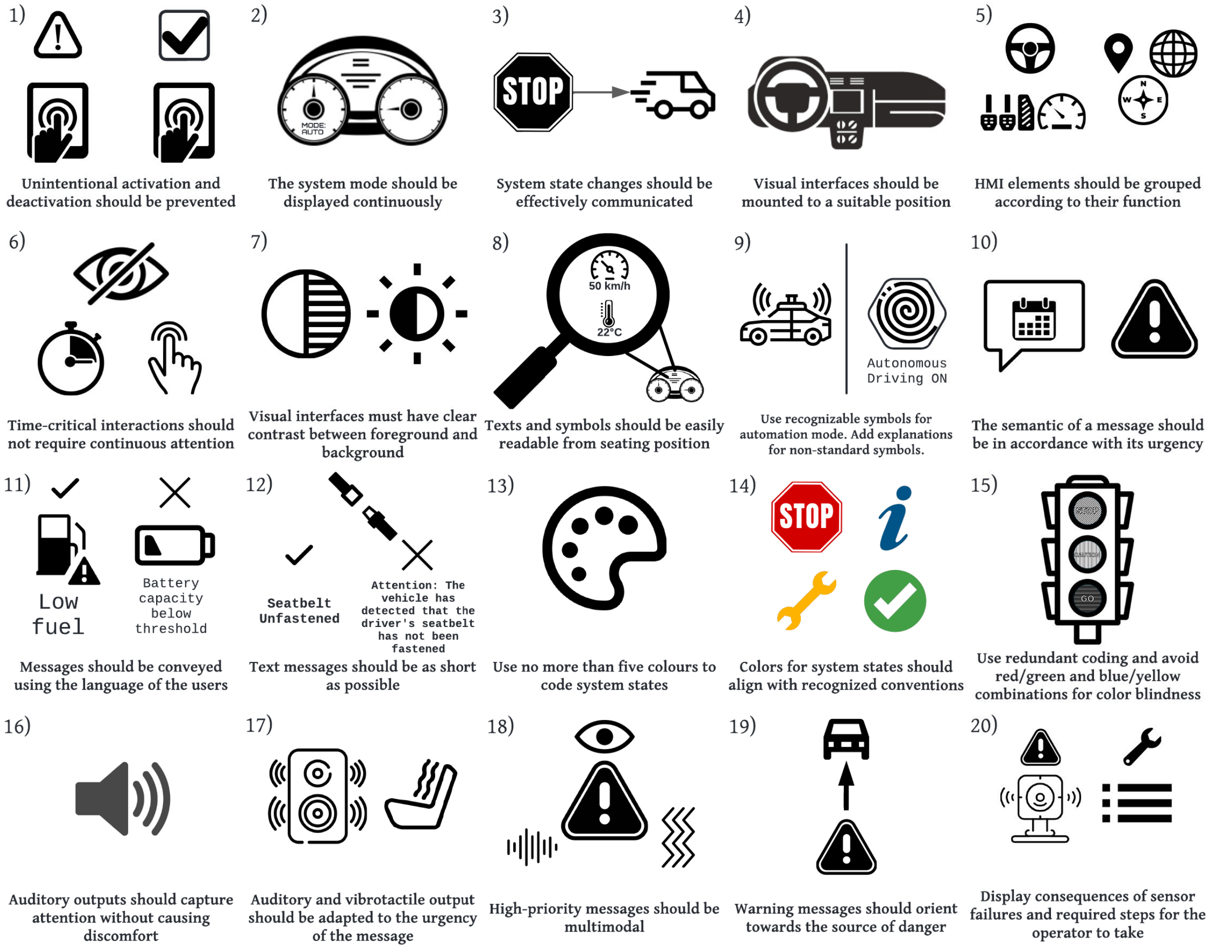


FIGURE 13. Guidelines for HMI design in autonomous vehicles, image based on Naujoks et al [44].

Despite the lack of specific regulation for HMIs in autonomous vehicles, there have been proposed guidelines and models that cover many aspects of the topic, such as design for comfort, wellness, and experience, among others, that are based on the demands of different previously stated regulatory bodies and associations or existing design models such as Benyon's "People-Activity-Context-Technology" (PACT) framework [41], [42]. One example of these proposed guidelines is shown in Figure 13; the contents of the guideline establish principles, recommendations, standards, criteria, and verification methods to guide the development of HMIs in autonomous vehicles. These guidelines have been evaluated by a workshop on evaluation methods for autonomous vehicles [43], and reflect multiple aspects that have been experimented with for the design of HMIs in autonomous vehicles.

V. LITERATURE REVIEW ON HMIs FOR AUTONOMOUS VEHICLES: EXPERIMENTAL PLATFORMS, TECHNOLOGIES AND PROGRESS BY DOMAIN AREA

In this section, interesting experimental vehicle platforms, using internal and external HMIs, are presented for different purposes identifying their characteristics and performance indexes. Technologies based on Artificial intelligence and novel actuation systems used for HMIs are detailed. Then, an overview of the use of biometrics technologies for HMIs is presented, analyzing the main interaction principles that are commonly developed for driver assistance systems. Finally, a review of different current specific applications of HMI technology in autonomous vehicles is demonstrated.

A. EXPERIMENTAL PLATFORMS FOR HMI DESIGN IN AUTONOMOUS VEHICLES

Simulation and experimental platforms have been developed to test and evaluate design concept performance reliability for both internal and external HMIs. For internal HMIs, as shown in Figure 14, they range from the use of simple driving simulators, where a monitor is used for studying the driving style of a driver, to cabin simulators that emulate the interior of an autonomous vehicle. In a cabin simulator, the point of view is shown in front of the cabin's windshield and different sensors inside the cabin are used to capture the passengers' perception. During these simulations users are typically presented in situations where automated driving is present and an external condition is introduced for the HMI to inform the user that attention is required, then the elements of the interface are presented either via the simulation or physically at the user's side to evaluate how the experimental users react and regain control of the vehicle [63]. Some of the parameters that are tested for internal HMI experiments include reaction times and take-over times, sometimes including additional details regarding the actions users do after taking control of the vehicle such as speed changes or gaze positions while driving [64]. Additionally, authors may also gather subjective information about the experiment subjects' perceived safety, performance reliability, and acceptance of the experimental platform through the use of evaluation ratings that can be used to enhance the platform by changing, adding, or subtracting elements based on users feedback [65], [66].

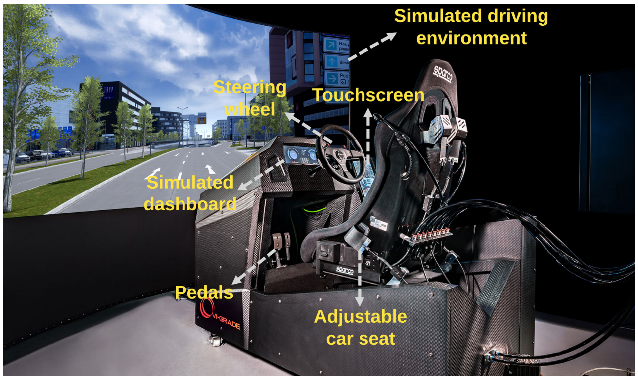


FIGURE 14. **Simulation cabin setup "COMPACT simulator" manufactured by VI-grade for evaluating internal vehicle HMI [67].**

Experiments for external HMIs (eHMIs) are similar in the use of simulation platforms. In this case, there is a prevalent use of simple computer simulations to simulate pedestrians in crossing situations, however, there are cases where the use of technologies such as virtual reality can enhance the simulation to produce more reliable results [59]. However, in contrast to experiments with internal HMI designs, as seen in Figure 15, external HMI experiments have had on-field tests with functional physical eHMI concepts for autonomous vehicles to evaluate their effectiveness under certain experimental conditions, primarily perceived safety and performance reliability from pedestrians [68], [69].

Table 1 shows different experiments presented in literature regarding internal and external HMIs, specifying the type of HMI that was experimented on, the experimental platform that was used for testing, and the characteristics of the HMI that were evaluated with their respective performance indexes. It can be observed that internal HMI experiments tend to solely use simulations to test design concepts, testing graphical elements displayed in the HMI with some experiments analyzing the use of auditory feedback. In the case of external HMIs, there is a mixture of both simulation and on-field testing platforms to evaluate design elements. Specifically, there is a focus on analyzing the effectiveness of visual elements for eHMIs to ensure performance reliability in pedestrians during crossing situations.

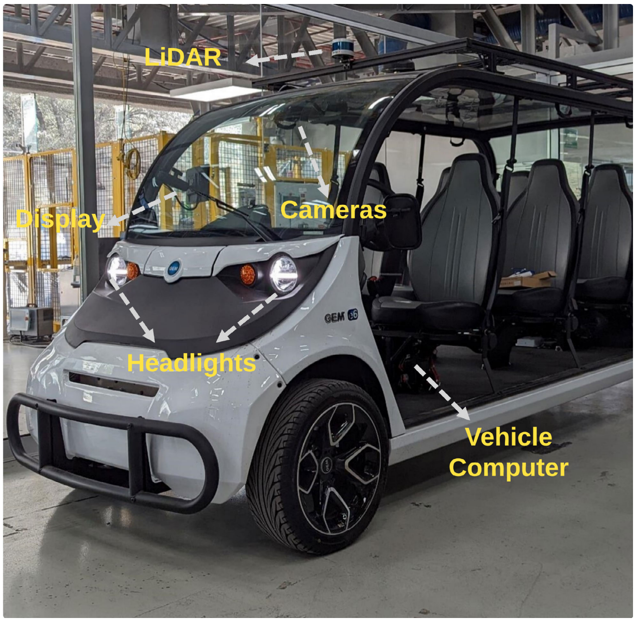


FIGURE 15. **On-field experimental autonomous vehicle platform to evaluate HMI elements at Tecnológico de Monterrey.**

Table 1 can be used to compare the recent experimental vehicle platforms with internal or external HMIs, by identifying the performance indexes used to determine the evaluation criteria proper for both HMI design concepts. Evaluating the effectiveness of HMIs in autonomous vehicles requires robust methodologies and standardized frameworks to ensure reliability and validity. Both types of HMIs are predominantly evaluated focusing on metrics such as interaction duration, perceived performance reliability, and ease of use and understanding. These methods allow for controlled testing conditions but may not fully capture the complexities of real-world interactions.

In addition to minimizing driver distraction and ensuring intuitive interaction, it is essential to consider how end-users perceive and interact with HMI systems in autonomous vehicles. Various studies have utilized user rating evaluations to assess the usability, attractiveness, and effectiveness of HMI designs. For instance, research has employed online surveys with industry experts to evaluate multimodal HMI frameworks by measuring hedonic and pragmatic qualities. Other studies have implemented simulation environments to evaluate system usability, understandability, and potential overreliance on automation, employing scales for task load assessment. These evaluations provide insights into user preferences, highlighting the importance of designing HMIs that are not only functional but also align with user expectations and comfort levels.

An opportunity area for both types of HMI research is the lack of emphasis on analyzing the effects of auditory stimulus for safety and performance reliability perception. For internal

TABLE 1. HMI simulation and experiments categorization.

Study	Year	HMI Type	Experimental Platform	Tested characteristic	Performance indexes
[63]	2015	Internal	Computer simulation	Graphical elements	Take over time
[66]	2016	Internal	Computer simulation	Graphical and interactive elements	Interaction duration and users' perceived performance reliability, performance, ease of use and stressfulness
[70]	2016	Internal	Simulation cabin	Graphical elements	Users' perceived usefulness and satisfaction
[51]	2016	Internal	Computer simulation	Graphical elements	Users' perceived usefulness, ease of use and comprehension
[50]	2017	Internal	Computer simulation	Graphical elements	Comprehensibility ratings
[47]	2017	Internal	Simulation cabin	Graphical elements and auditory output	Monitoring ratio, perceived usefulness and perceived visual workload
[71]	2018	Internal	Simulation cabin and computer simulation	Graphical elements	User experience, reaction time, number of collisions
[52]	2018	Internal	Simulation cabin	Augmented reality visual elements	Take over time, eyes on windshield time, brake reaction time, lane change time, head angle
[64]	2019	Internal	Simulation cabin and computer simulation	Graphical and auditory elements	Average trajectories after take over request, and reaction time
[48]	2020	Internal	Computer simulation	Graphical elements	Take-over times
[33]	2021	Internal	Computer simulation	Graphical elements	User experience rating
[65]	2021	Internal	Simulation cabin	Graphical elements	Users' perceived performance reliability
[46]	2021	Internal	Simulation cabin	Interior design concept	Take-over times and situational awareness ratings
[53]	2021	Internal	Computer simulation	Augmented reality visual elements	Users' state anxiety, situation awareness rating, acceptance, take-over times, perceived controllabillity, deceleration and lateral control after take-over
[49]	2022	Internal	Simulation cabin	Auditory and tactile elements	Take over time, reaction time
[42]	2022	Internal	Prototype concepts	Graphical and interactive elements	User experience rating
[45]	2022	internal	Computer simulation	Graphic elements	User experience, perception and comprehension
[69]	2019	External	On-field testing	External visual elements	Perceived safety, performance reliability, acceptance and understanding
[68]	2020	External	On-field testing	External visual elements	User experience and perceived safety
[55]	2021	External	Virtual reality lab and computer simulation	External visual elements	Pedestrian and gaze behaviour
[54]	2021	External	On-field testing	External visual elements	User experience questionnaire
[58]	2021	External	Computer simulation	External visual elements	User experience rating and response time
[57]	2021	External	Computer simulation	External visual elements	User questionnaire
[59]	2021	External	Computer simulations	External visual elements	Visibility density and efficiency
[60]	2021	External	On-field testing	External visual and auditory elements	Trust, perceived safety, pragmatic quality, social presence, and transparency
[56]	2022	External	Visual questionnaire	External visual elements	Users' preference rating
[61]	2022	External	On-field testing	External visual elements	User's perceived information clarity and safety

HMIs, the lack of on-field experimental platforms may be considered a limitation due to the requirement elevated costs of obtaining an autonomous vehicle for research purposes and the programming complexity it may involve, which in contrast with external HMI tests, typical experiments use conventional vehicle platforms, seemingly instrumented to be automated to convey an autonomous nature. These limitations may impact the results of the experiments since users are in a safe, constrained environment that is different from real life. The developments in autonomous vehicle technology could increase their access as experimental platforms for validation of HMI concepts that could improve drivers, passengers, and pedestrians' safety and acceptance.

B. ARTIFICIAL INTELLIGENCE TECHNOLOGIES IN HMI DESIGN FOR AUTONOMOUS VEHICLES

As the level of automation increases, Artificial Intelligence (AI) technologies, in the form of Machine Learning (ML), need to be implemented, as the HMI should accurately diagnose the situation in order to know if it's possible to switch between human and machine while driving the vehicle, as human override is still an option in high automation [72]. Some of the AI technologies used to reinforce the interaction between the user and the autonomous vehicle and their research interest in the last 5 years based on an additional SCOPUS search, shown in Figure 16, are the following:

- **Natural Language Processing (NLP):** AI will foster NLP integration allowing users to interact with the vehicle using voice commands, enabling hands-free operation for tasks such as navigation, entertainment control, and communication [73].
- **Predictive analytics:** AI methods can study user behavior, preferences, and contextual data to anticipate user needs and proactively suggest actions or adjust vehicle settings to improve comfort, convenience, and safety [74].
- **Situational awareness:** By integrating data from on-board sensors, cameras, and external sources, AI can provide contextual awareness to the vehicle interface, enabling adaptive responses to changing driving conditions, traffic situations, and user requirements [75].
- **Personalization:** AI-powered personalization features can tailor the vehicle interface to individual user preferences, including screen layouts, menu structures, and content recommendations, improving the overall user experience [76].
- **Cognitive load monitoring:** AI algorithms can monitor the cognitive load of the driver and passengers by analyzing factors such as gaze, facial expressions, and physiological signals, providing feedback or assistance to reduce distractions and ensure safe driving [77].
- **Predictive Maintenance:** AI-powered predictive maintenance systems can monitor vehicle performance data in real-time, detect potential problems before they escalate, and recommend preventative maintenance actions to optimize vehicle reliability and lifespan [78].

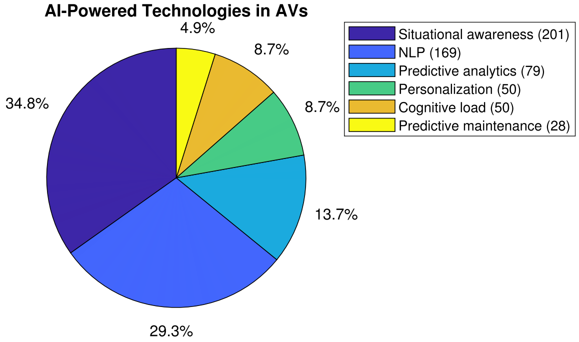


FIGURE 16. Research distribution of AI-powered technologies in AVs over the past five years, based on SCOPUS data. The number of related research projects is in parentheses.

Examples of complex systems include an ADAS, which may use a Robot Operating System (ROS) and a Car Learning to Act (CARLA) simulator to receive and process Application Programming Interface (API) data based on Photoplethysmography (PPG) and Galvanic Skin Response (GSR) biosignals for emotion recognition and so assess whether a driver is capable of performing manual driving [79].

AI technologies can also enhance the real-time adaptability and learning capabilities of HMIs, enabling more effective interaction between users and autonomous vehicles. Recent AI-driven breakthroughs have significantly improved the ability of HMIs to adapt to changing environments and user needs in real-time.

One example of such advancements is the application of deep learning models to enhance pedestrian detection systems in autonomous vehicles which can improve the accuracy of identifying pedestrians and predicting their movements, leading to safer and more responsive autonomous driving behaviors [80].

Another relevant advancement involves the use of deep learning and multimodal data fusion to improve the detection of emergency vehicles. This approach combines multiple data sources to provide timely and accurate alerts to drivers, enabling quick and appropriate responses in critical situations so that HMIs could have the potential enhance situational awareness and safety for both vehicle occupants and other road users, ensuring a more reliable interaction with the environment [81].

C. BIOMETRICS IN AUTONOMOUS VEHICLES HMIs

The integration of biometric sensors in HMIs is vital to implement supervision methodologies (camera vision, vehicle monitoring, and lane monitoring), and carry out permanent tests to evaluate the levels of attention, fatigue, and workload status of the drivers and/or passengers, as shown in Figure 17, on which complex algorithms, as well as intelligent processing, are both required in order to provide reliable autonomous functions [72]. When processing these biometric features with additional ML algorithms, such as Support Vector Machine (SVM) and AdaBoost, it is possible to detect cognitive load using gaze direction, head orientation, pupil area and diameter, and R-R interval (distance between heartbeats), in order to assess driver's state on having a conversation while driving, ordinary driving and doing arithmetic tasks [82].

Tests are currently being done on AV simulated environments, which include Virtual Reality (VR) porting and motion platform integration in order to apply tilt and pitch angles and thus provide, finally, predicting a *hazard index* based on GSR [83]. Furthermore, being able to affect perception time, response time, internal vehicle processing time, external transmission time; and although there have been many HMI modalities; the best performance and most usability are achieved when having a functional autonomous level 5 vehicle, as not only communication time is eliminated, but also driver time [84].

The most relevant biometric sensor technologies and their research interest in the last 5 years based on an additional SCOPUS search, shown in Figure 18, are categorized as follows:

- **Facial Recognition:** Utilized for driver authentication, monitoring driver attentiveness, detecting drowsiness, and providing personalized settings based on recognized individuals [85].
- **Eye-Tracking:** Monitors the driver's gaze direction, pupil dilation, and blink rate to assess attentiveness, fatigue, distraction, and intention to provide timely alerts or interventions [86].
- **Heart Rate Monitoring:** Measures the driver's heart rate to detect stress, fatigue, or medical emergencies, enabling appropriate responses and adjustments to driving conditions [87].
- **Voice Recognition:** Allows for hands-free interaction with the vehicle's controls, enabling voice commands for navigation, entertainment, climate control, and communication [88].
- **Gesture Recognition:** Enables intuitive control of HMI functions through hand movements or gestures, enhancing user experience and reducing cognitive load [89].
- **Electroencephalography:** Measures brain activity to assess cognitive workload, attention levels, and emotional states, providing insights into the driver's mental state for adaptive HMI responses [90].
- **Skin Conductance Sensors:** Detect changes in skin conductivity to gauge stress levels, emotional arousal, or discomfort, informing HMI adjustments and intervention strategies [91].

Literature shows that biometrics used in HMI application tests include PPG, which is an optical sensor placed within the driver's index finger and can detect blood pressure, volume change, and heart activity; as well as GSR, which is acquired to measure the skin conductance via either the middle and ring fingers or by sensors mounted within the steering wheel or the seat belt [92], thus being able to gather sweat secretion and body temperature, further predicting driver's emotions, workload state, and fitness level [79]. In addition, standard and thermal cameras can be used to gather vision data to indicate stress level, fitness level, emotional state, and driver intention [92]. On the other hand, more wearable and obtrusive devices include detecting brain waves based on Electroencephalography (EEG), which can predict stress and mental fatigue state [93]. An additional non-conventional unobtrusive sensor is pressure cells, which can detect whether the driver is in a non-optimal position by measuring non-uniform pressure distribution [94], also combined with video sensors [95].

Although respiration rate and HR were not useful in [96] for detecting concentration, it can identify abnormal conditions that would trigger a takeover scenario (such as drowsiness or shock), in which a level 3 highly automated vehicle would follow the complex takeover strategy described in Figure 19. The set of Emergency maneuvers (EM) and Minimum Risk Maneuver (MRM) is critical in order to avoid an accident, based on biometrics to determine whether the driver is capable of manual driving [96].

Interaction with the HMI requires input from hand and fingers based on sensors; this includes Infrared (IR) Systems, based on infrared sensors to track a position; Wearable Device systems, attached directly to them; Internal Measurement Unit (IMU) Systems; as well as Remote Control-Based Points, using existing remote control devices and pointers [97].

D. ACTUATOR TECHNOLOGIES IN HMIs FOR AUTONOMOUS VEHICLES

Regarding the representation of this data collected by biometrics, actuator technologies allow the system to present information or related alerts to the users through HMIs that contribute to creating immersive, intuitive, and user-friendly HMI experiences in autonomous vehicles, enhancing safety, comfort, and convenience for passengers and drivers alike [98]. These actuator technologies and their research interest in the last 5 years based on an additional SCOPUS search, shown in Figure 20, can be categorized as follows:

- **Displays:** Various types of displays, including LCD screens, OLED displays, Heads-Up Displays (HUDs), and Augmented Reality (AR) displays, provide visual feedback to the driver or passengers regarding navigation, vehicle status, surroundings, and entertainment [99].
- **Haptic Feedback Systems:** Incorporate tactile feedback mechanisms such as vibrating motors, actuators, or electrostatic forces to provide physical sensations to the user, enhancing the perception of touch and interaction with touchscreens, buttons, or controls [100].
- **Auditory Feedback Systems:** Utilize speakers and sound generation technologies to deliver auditory cues, alerts, notifications, and voice prompts to communicate information effectively to the driver or passengers [101].
- **Steering Wheels and Pedals:** Although traditional in-car controls, these actuator technologies may incorporate haptic feedback or force-feedback mechanisms

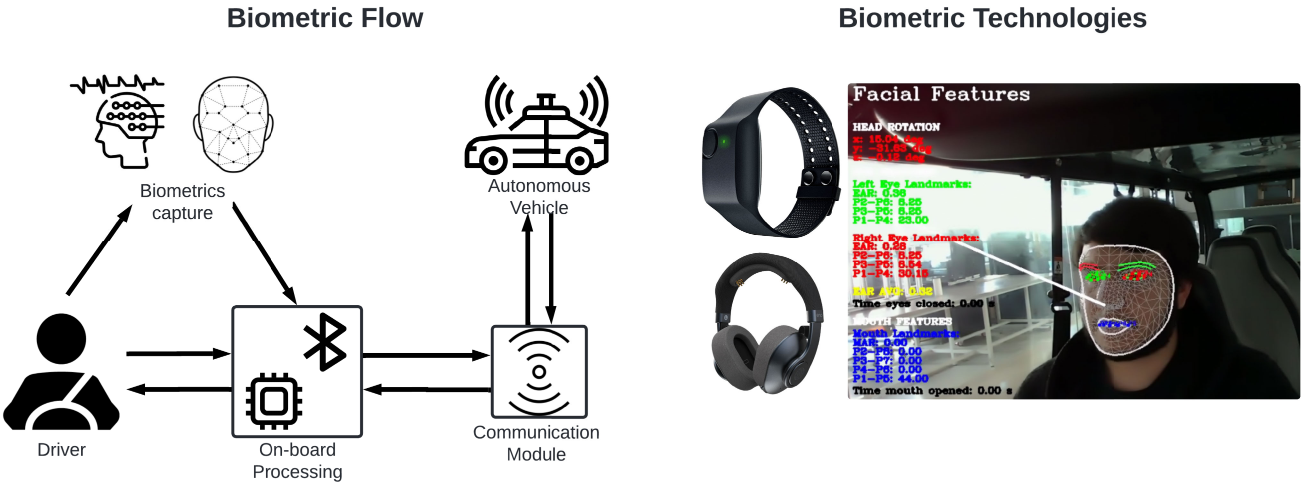


FIGURE 17. Flow diagram of ADAS integrated with biometric devices.

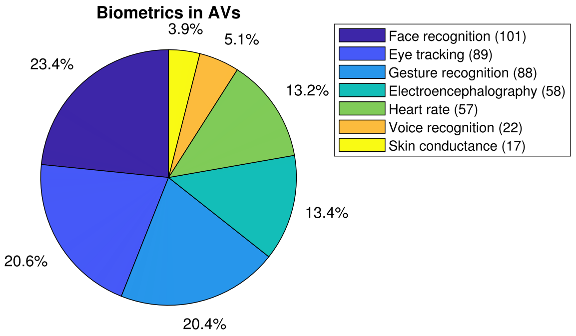


FIGURE 18. Research distribution of biometric technologies in AVs over the past five years, based on SCOPUS data. The value in parentheses indicates the number of related research projects.

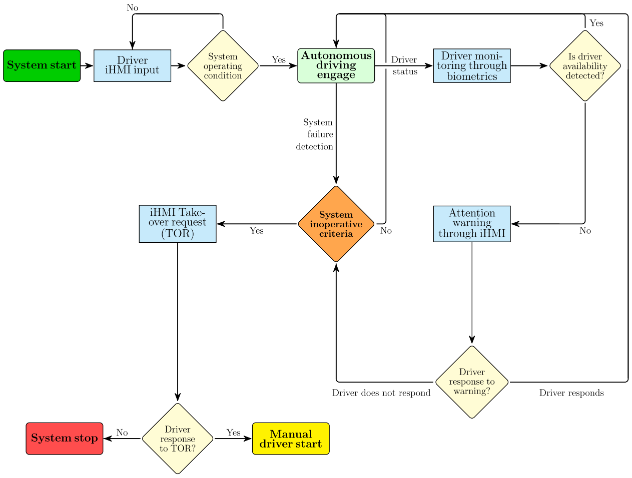


FIGURE 19. Flow diagram for a Level 3 automation decision-taking takeover strategy, involving driver availability detection through biometrics.

to enhance driver interaction and provide tactile cues during autonomous driving modes or manual interventions [102].

- **Touchscreens and Touch-sensitive Surfaces:** Enable intuitive interaction with HMI controls and interfaces through touch gestures, multitouch capabilities, and customizable user interfaces for accessing vehicle functions, navigation, entertainment, and climate control [103].
- **Ambient Lighting Systems:** Utilize LED lighting elements strategically placed within the vehicle's interior to provide visual cues, notifications, mood lighting, and personalized ambiance, enhancing user experience and comfort [104].
- **Dynamic Seating and Interior Configurations:** Employ actuators and motors to adjust seating positions, seat configurations, and interior layouts dynamically, optimizing comfort, accessibility, and space utilization based on user preferences, driving modes, or autonomous driving scenarios [105].

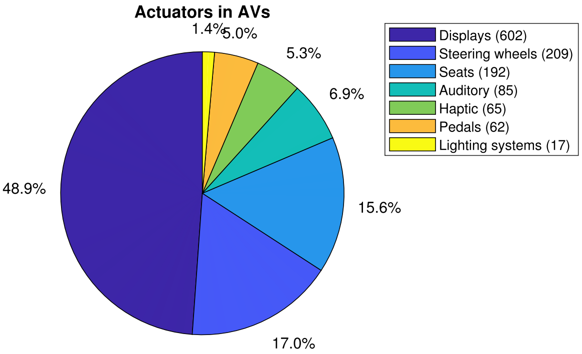


FIGURE 20. Research distribution of actuator technologies in AVs over the past five years, based on SCOPUS data. The value in parentheses indicates the quantity of related research projects.

Prototype implementations of these technologies include an AirGesture system, in which the driver has to remember a set of gestures [106], as well as the BullsEye system, which gathers relative positions of screen items [107].

Information detected using biometrics, such as a high cognitive workload, has to be communicated to the driver; one alternative is to use tactile displays, as drivers are able to confidently interpret important information, such as pedestrian status warnings and headway reduction signals when using higher urgency patterns, while still having short reaction time during a continuous driving task [108]. Regarding the visual architecture of the HMI system and its evaluation based on the driver's Decision-Making Time (DMT), there are some researches that study the DMT index when vehicles are expose to a risk situation in order to analyze the performance reliability of the HMI [109]. In addition, there is limited documentation of the Open Interfaces (OAS) focused on human-vehicle interactions, as the User Interface (UI) is very much based on smartphone use and not vehicle use; moreover, most of the cases interfaces reside in interoperability of the In-vehicle Information (IVI) with mobile devices [110].

E. SPECIFIC APPLICATION OF AUTONOMOUS VEHICLES HMIs

Even though there's active current research regarding HMI technologies for autonomous vehicles, there are some applications where these types of vehicles are being deployed. The use of these platforms serves as a precedent for experimenting and evaluating developing technologies in autonomous vehicles including interface design concepts.

- **Personal:** Currently, most of the personal use automated vehicles are at an SAE level of automation between 2 and 3, some examples include the Mercedes E Class, Tesla Model S, Volvo V90, BMW 7 series, and VW Passat, each with their own approach at monitoring and displaying internal and external information to their users through an interface [111]. Research regarding HMI design involves analyzing these platforms' interface design through the proposed transparency assessment method to estimate their understandability to identify critical elements of their HMIs that make users comfortable and knowledgeable of the systems [112], [113].
- **Commercial:** Autonomous vehicles have begun to provide commercial applications for users, one of these examples relies on using them for providing transportation services. Some examples include Uber cars with their XC90 and Fusion platforms and Google Car with their Prius platform, whose sensor setups offer autonomous transportation services with SAE level 4 automation capabilities, and their interface design have the objective of providing navigation and environmental information to their users [114]. Another commercial use of autonomous vehicles involves delivery applications, where delivery robots provide delivery services from a warehouse to a customer's living place. Research in HMI technologies for these robots involves the use of external interfaces for the robot to indicate its navigational intent to pedestrians through text and lights, presenting information about its context [115].
- **Military:** Autonomous vehicles have many uses in military applications, including surveillance, inspection, logistics, and combat, among others which all need a network-based security application to integrate the required sources and services to function properly [116]. The design of proper interfaces for this application poses a challenge due to the increasing complexity and required tasks of the vehicles, which need much more computational resources not only for sensing and processing environmental information but also for coordination with additional vehicles that are deployed simultaneously. One example is the deployment of unmanned autonomous systems such as robotic platforms like UAVs, UUVs, or UGVs, whose human operators have had the challenge of using the real-time data obtained by these platforms to make decisions, and their interfaces should be able to anticipate disturbances while monitoring performance and responding to threats to ensure safety [117]. There is also a focus on designing interfaces to support the operation of as many complex UAVs as possible while reducing the number of operators needed, with the specific target of isolating cognitive processes and how sensory data is gathered within target environments [118].
- **Agricultural:** Multi-purpose autonomous vehicles are being deployed in agricultural environments to automate harvesting operations. Their adoption relies on their ability to be able to operate safely and avoid accidents, which is why research is focused on designing interfaces so that workers in the area can interact with the vehicle through the use of natural language, gestures, and portable devices for monitoring [119].

VI. DISCUSSION

Developments in automotive technology have led to current research in autonomous vehicles. One of the critical research areas focuses on the interaction between vehicles and users, which encompasses not only drivers and passengers but also external road users such as pedestrians and other vehicle drivers. These interactions aim to ensure safety and comfort by providing users with necessary information about the vehicle's status and its surroundings through the vehicle's interfaces.

Research in this area needs to be user-centered, addressing specific user needs inside and outside the vehicle, and considering external environmental elements that increase situational awareness. For instance, effective HMIs must provide clear and intuitive alerts to drivers during NDRTs to facilitate a smooth transition to manual control when necessary. These elements need to be communicated reliably through multiple stimuli, such as visual, auditory, and haptic feedback, to ensure a clear understanding of the situation. This approach enhances performance reliability and user acceptance, particularly with the increasing deployment of electric autonomous vehicles in urban areas.

The implementation of biometric technologies in HMIs is another significant area of development. These technologies monitor driver conditions during vehicle operation, generating alerts when needed and ensuring the decision-making process is not compromised by the vehicle's condition or external factors. For example, eye-tracking systems can detect driver drowsiness, while heart rate monitors can identify stress levels, ensuring timely alerts and interventions to maintain safety.

Currently, there are several challenges involved with the implementation of HMI technologies in autonomous vehicles, one of the most relevant is the lack of development of specific standardized protocols and regulations regarding these technologies. This lack of standards can cause difficulties and present obstacles to the implementation of developing technologies into a relatively new market such as autonomous vehicles. For instance, without standardized HMI protocols, a user familiar with one vehicle's interface might struggle with another, reducing confidence and slowing the adoption of autonomous vehicles. The development of standards tailored to HMIs for autonomous vehicles would help designers ensure consistency between designs so that users from different autonomous vehicle platforms can obtain familiar experiences within the vehicle. This would minimize the learning curve of interacting with the vehicle, such as the scenario where autonomous vehicles are used as a service for transportation by multiple companies, improving confidence and motivating the adoption of autonomous platforms. The creation of standards would also facilitate the interoperability between components of different manufacturers, which would allow for better integration and compatibility in this type of system. Standardization would also allow regulatory bodies to define minimum requirements and performance indexes for HMIs, reducing the risk of accidents and user errors.

Another relevant challenge lies in the availability of appropriate validation platforms for testing HMI designs. Researchers often resort to computer simulations and simulation cabins to test internal interfaces, which provide a controlled environment but may not reflect the complexities of real-life interactions. For example, simulation cabins like the VI-grade simulator can recreate the interior of an autonomous vehicle and project virtual test roads, but they might not capture the full range of user reactions seen in actual driving conditions. For external interfaces, virtual reality technology has been used to immerse test subjects in the role of pedestrians, providing better immersion and interactive environments. However, these simulations still have limitations in replicating real-life conditions dynamically.

Some researchers have managed to test external interfaces using physical validation platforms, ranging from simple autonomous vehicles to remotely controlled ones perceived as autonomous. These platforms allow for the evaluation of real-world interactions but come with significant economic and logistical challenges. They require substantial investment not only to acquire the platform but also to design infrastructure and implement safety measures. For instance, on-field testing platforms like those at Tecnológico de Monterrey involve high costs and complex coordination with authorities.

Addressing these challenges is crucial to ensure that HMI designs are thoroughly tested, validated, and capable of providing safe and effective driving experiences. Collaboration between researchers and industry, alongside the development of open-source platforms and standardization efforts, can help overcome these barriers and accelerate the advancement of HMI technologies in autonomous vehicles.

VII. CONCLUSION

The adoption of HMI technologies in autonomous vehicles offers numerous benefits that enhance their functionality and appeal in the market. Key benefits include enhanced safety through real-time feedback, alerts, and warnings, which mitigate risks and prevent accidents. Additionally, HMIs improve user experience by providing seamless access to vehicle status information, vehicle controls, entertainment systems, and personalized settings, which enhance comfort.

In terms of reliability, HMI systems in autonomous vehicles must incorporate key features such as redundancy and fault tolerance to ensure continuous operation despite sensor failures or software glitches. Additionally, user feedback mechanisms, usability testing, and validation processes should ensure that HMI systems meet user expectations and perform reliably in real-world scenarios.

Moreover, external HMIs play a critical role in communicating the vehicle's status and intentions to pedestrians and other road users, enhancing overall traffic safety. Effective external HMIs ensure that pedestrians receive clear and timely information about the vehicle's movements, reducing the likelihood of accidents and improving the interaction between autonomous vehicles and their environment.

Looking towards the future, several research directions and emerging trends in HMI design for autonomous vehicles need to be addressed. Future research should explore the integration of artificial intelligence and machine learning to create adaptive and predictive HMI systems that can anticipate user needs and preferences, taking also into account the external conditions in which the AV operates by identifying pedestrians and other vehicles' movements to act and communicate with them accordingly. Additionally, the development of more immersive and intuitive interfaces, such as those implementing augmented reality technologies, could significantly enhance user experience and engagement.

Research in HMI design for autonomous vehicles should also consider the integration of emerging technologies such as deep learning-based detection systems for identifying pedestrians, vehicles, and traffic conditions in complex urban environments which could improve AVs' ability to adapt to dynamic situations. Additionally, exploring real-time traffic management solutions using technologies that are embedded into the road infrastructure or external surveillance systems and predictive algorithms with the support of cloud computing will further address the challenges of navigating diverse environments. Finally, research should consider working towards standardizing HMI technologies across manufacturers to ensure an effective adoption in the market with a common direction.

Unanswered questions in the field include the long-term impact of HMI technologies on driver behavior and safety, the ethical implications of user data collection through the use of biometric technologies and its usage, and the potential for standardizing HMI designs across different vehicle manufacturers. Addressing these questions will be important for advancing the field and ensuring the successful adoption and acceptance of autonomous vehicles in the market.

Overall, the integration of advanced HMI systems in autonomous vehicles delivers a wide range of benefits, incentivizing the adoption and acceptance of autonomous vehicles. By addressing current challenges and focusing on future research directions, the field can continue to evolve and provide safer, more efficient, and more enjoyable driving experiences for all users.

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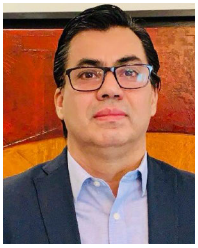

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