Human-Machine Interfaces in Safety-Related Cooperative Driving Automation Systems

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***Abstract*—The main objective of connected vehicles is to significantly improve safety for travel participants and nearby people. Cooperative Driving Automation denotes the set of autonomous applications requiring cooperation among connected vehicles, including those with driving automation features engaged. As the operational purpose of the cooperation depends on the application class and the level of driving automation, it follows that the communication strategies and, therefore, the design principles of the human-machine interfaces of participating vehicles must change as well. However, the literature is missing a standardized and coherent strategy for the design and implementation of these interfaces, which may have undesirable impacts on the risk reduction profile of cooperative applications. This paper wants to be a first step in the definition of suitable design principles for such interfaces. We contribute an overview of related solutions providing a selection of relevant works, and we synthesize a set of fundamental human-machine interface design principles for safety-related cooperative applications, hypothesizing an inverse relationship between the level of driving automation and the need for active approaches to maximise the safety of connected vehicles and nearby road users.**

***Index Terms*—ADS, CDA, HMI, V2X, VRU**

I. Introduction

Cooperative Driving Automation (CDA) is defined in the SAE J3216 standard [1] as a set of autonomous applications aimed at improving safety and traffic flow by means of cooperative communications among multiple vehicles in proximity to each other, also including nearby road users like pedestrians, cyclists, vehicles with driving automation features engaged, etc.

The operational purpose of the cooperation depends on the application class and the level of driving automation, and it can be supportive or enabling, for instance, providing timely information to the driver (supporting) or automatically seeking an agreement on a course of action among automated driving vehicles (enabling). Likewise, Human-Machine Interface (HMI) solutions can go from having an informative-only approach, like transparently communicating the decision model of an autonomous system to increase user trust, to representing an active and essential component in the decision system of the driver, such as by presenting a big and noisy "brake" message in case of an expected collision or nudging the driver's input towards re-entering the bounds of a lane by applying a rotational force to the steering wheel. CDA is classified by SAE into four levels depending on the amount of cooperation involved. Similarly, autonomous driving falls into six categories based on the degree of autonomy involved. HMI systems, on the other hand, lack a standardized and coherent strategy for their design and implementation in this context despite being the actual medium through which users interact with those systems. This may be especially critical for safety-related cooperative applications, where we would argue that the efficacy of an interface solution is strictly related to the reduction (or not) of accident risk.

This paper attempts a first step to bridge the gap. Section II summarizes CDA cooperation classes and their intersection with automation levels. Section III overviews related HMI solutions. Section IV proposes suitable HMI principles for the design of proper interfaces, while Section V concludes the article by discussing future directions for this line of research.

II. Cooperative Driving Automation

CDA uses Vehicle-To-Everything (V2X) communications to enable cooperative behaviors among entities participating in a vehicular network. Four CDA cooperation classes have been defined based on the growing amount of cooperation they involve, namely:

- Class A: Status-sharing (Least amount of cooperation)
- Class B: Intent-sharing
- Class C: Agreement-seeking
- Class D: Prescriptive (Most amount of cooperation)

The entities involved in a network using CDA may be autonomous, partly autonomous, or manual, and in the former two cases, automation features may or may not be engaged. Regarding autonomous driving, SAE defines six automation levels, listed here in order of increasing autonomy:

- Level 0: No driving automation

This study was carried out within the MOST – Sustainable Mobility National Research Center and received funding from the European Union Next-GenerationEU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR) – MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.4 – D.D. 1033 17/06/2022, CN00000023). This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

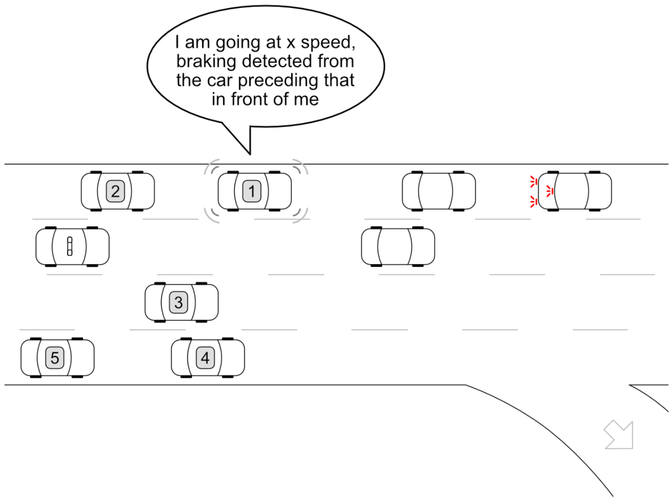

Fig. 1: Status-sharing cooperation example

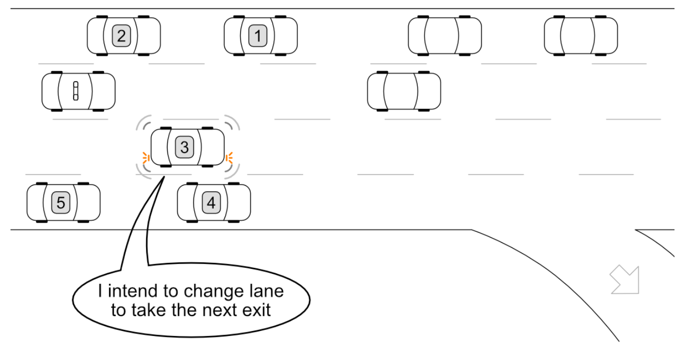

Fig. 2: Intent-sharing cooperation example

- Level 1: Driver assistance with longitudinal or lateral vehicle motion control
- Level 2: Partial driving automation with longitudinal and lateral vehicle motion control
- Level 3: Conditional driving automation
- Level 4: High driving automation
- Level 5: Full driving automation

Throughout the article, we will use the terms Driving Automation System (DAS) to indicate L1-L2 technologies and Automated Driving System (ADS) to indicate L3-L5 systems. CDA may enhance the performance of vehicles with automation features engaged, facilitating safety and efficiency. However, *cooperation differs based on the level of driving automation* [1]. More specifically, CDA provides limited cooperation to DAS (L1-L2) as the vehicle relies on the human driver to perform some functions and supervise the driving task. Instead, CDA can supply more consequential features to ADS (L3-L5), given that the vehicle is in charge of the complete driving task, at least under defined conditions. In the latter cases, we denote as a Cooperative Automated Driving System (C-ADS) the whole setup in which CDA and ADS join forces.

The following subsections detail the four CDA cooperation classes, discussing the risk reduction that each entails with regard to the automation level.

A. Status-Sharing Cooperation

Status-sharing cooperation can be outlined by the sentence *“Here I am, and here is what I see”* [1], and it is depicted in Figure 1. Status-sharing is the *sharing of the current state* from the point of view of the sending entity. It is a one-way communication, meaning that the sender transmits information about itself and the surrounding environment for potential utilization by receiving entities without an interaction ensuing from the latter. Conceptually, this class includes (but is not limited to) the beaconing applications in V2X protocol stacks. Basic Safety Messages and Cooperative Awareness Messages, defined by SAE and ETSI, respectively, are examples of cooperative status-sharing messages [2]. However, status-sharing cooperation may include cases in which the shared information also comprises intelligence from roadside infrastructure, e.g., ‘a pedestrian is approaching the crosswalk’, as well as attributes of other vehicles, e.g., the velocity of the vehicle immediately in front or a braking event of the vehicle leading the latter, which can be for instance detected by cameras.

It is important to highlight that CDA devices not having control over their *agents*’ actions may also engage in status-sharing cooperation. Examples of such agents include pedestrians and drivers of conventional vehicles. Here, HMI can play a primary role in conditioning the agents’ response in DAS (L1-L2) devices, while it has limited relevance, e.g., it can be used to increase trust in automation, in ADS (L3-L5) vehicles.

B. Intent-Sharing Cooperation

Intent-sharing cooperation can be outlined by the sentence *“This is what I plan to do”* [1], and it is depicted in Figure 2. Intent-sharing is the *sharing of an intended future state* of the sending entity. Like status-sharing, communication is one-way, and receiving entities may or may not act on the shared intent. The example in Figure 2 depicts a non-CDA intent-sharing in the form of a turn signal (which is itself an HMI) coupled with a CDA intent-sharing message that can augment or substitute the information given by the turn signal. Intent-sharing may be based on information from previous status-sharing, and, similarly to the latter class, CDA devices without control over their agents’ actions may still engage in intent-sharing cooperation.

As noted in the J3216 standard, all involved entities are expected to conduct competent operations regardless of others’ actions. CDA-related HMI can again condition the agents’ response in DAS devices, e.g., by highlighting the actions that would be required to accomodate other vehicles’ intentions, and reassure passive ADS vehicles’ agents about both the

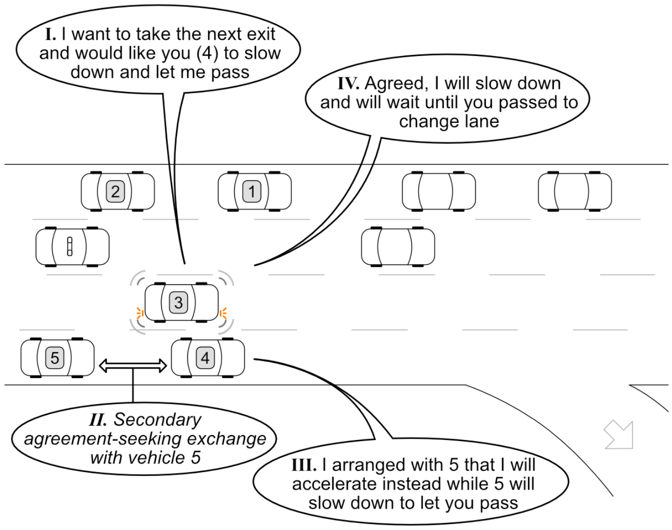

Fig. 3: Agreement-seeking cooperation example

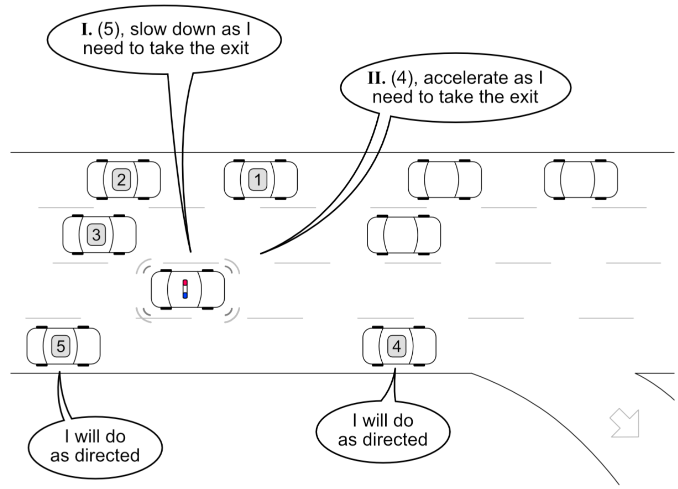

Fig. 4: Prescriptive cooperation example

competence and the appropriateness of the automated vehicle actions.

C. Agreement-Seeking Cooperation

Agreement-seeking cooperation can be outlined by the sentence *"Let's do this together"* [1], and it is depicted in Figure 3, where Roman numerals indicate the sequence of events in time. Agreement-seeking is a *message exchange aimed at locally converging to an agreed future state*. Therefore, the communication is two-way, and it can encompass secondary agreement-seeking cooperation exchanges upon which the original cooperation may depend, as shown in step II of Figure 3. In addition, an agreement-seeking behavior may be based on information from previous status- and intent-sharing.

In classes A and B, transmitting or receiving entities are not required to have the capability to act on the information provided, nor is any consent required for them to act upon it. In contrast, class C requires participants to be engaged in cooperation instead of being only able to be passive recipients of shared information. This implies that for CDA devices to cooperate and agree on an action plan, they need both the ability to leverage V2X messages for these purposes as well as the consent of their agents for them (or the agents themselves) to act upon the agreed plan. In other words, CDA agents hold the authority for action and can preemptively grant the temporary transfer of this authority to C-ADS devices. Given that with ADS vehicles the cooperation may be automatic while DAS devices require the intervention of the CDA agent, HMI interfaces must serve very different purposes and thus require different design approaches. Furthermore, a central tenet of agreement-seeking is that CDA device agents may not follow a planned action, so all entities are still expected to conduct competent operations regardless of others' actions, which requires the HMI to improve agents' response capabilities instead of being deleterious. In addition, CDA devices that do not exert control over their agents' actions may not be able to participate in agreement-seeking cooperation and can introduce unforeseen changes in local CDA states.

D. Prescriptive Cooperation

Prescriptive cooperation can be outlined by the sentence *"I will do as directed"* [1], and it is depicted in Figure 4. Prescriptive cooperation means *adhering to a future state*. Figure 4 shows a prescribing CDA device (or device agent) and adherent receiving CDA devices (or devices' agents), the latter confirming the adherence to directed actions with acknowledgment messages. As such, communication is shown to be bidirectional, but functionally speaking, communication is only one-way. Proper two-way communication may be included if the cooperation is based on previous agreement-seeking; in addition, class D may also use status- and intent-sharing cooperation, mainly to provide context to adhering devices.

CDA devices may only participate in prescriptive cooperation if they exert control over their agents' actions, at least under specific circumstances such as in conditional driving automation (L3), in which human override may be required if the system is unable to execute the task. Affected entities rely on a pre-existing agreement to adhere to instructions from an external authority without needing further consent granted from their agents. In any case in which a CDA device agent may be involved, the HMI design should aim at increasing its situational awareness (an example in which no CDA device agent may be involved is the case of an emergency vehicle directing a traffic control signal to change phase, in order to facilitate faster transit for the emergency vehicle itself [1]).

III. Related Human-Machine Interfaces

Over the past decade, a substantial number of studies have been conducted on human-machine interaction in the context of partially and highly automated driving. The primary emphasis of this research has been on developing and evaluating strategies for the interaction between the human driver and the vehicle. Within this framework, the research has focused on situations that have the potential to significantly affect safety, such as the transition of control from humans to automated agents and vice versa. The so-called ”take-over request” has undergone thorough consideration with regard to design techniques [3], response times [4], and post-takeover performance [5]. Recently, the greater availability of data from many traffic sources has allowed for the testing of more advanced interaction techniques. These strategies make use of the information gathered from distributed sensors and transmitted through the communication infrastructure. The availability of this information brings two significant benefits: firstly, it helps to overcome the limitations associated with traditional sources of information used for driving perception, such as the driver's ability and the vehicle's sensors, and provides access to additional information that is typically unavailable due to distance or obstruction [6]; secondly, it enables users to have more timely and accurate access to traffic data, allowing for more precise and sophisticated visualisations, thus supporting decision-making and the effectiveness of execution [7]. Tailored interaction strategies involving the combination of HMIs and V2X communication technologies have the potential to positively influence safety perceptions and behaviors among road users. While CDA taxonomy is not commonly used in the context of HMI research and current systems are not organized by classes of cooperation, it is worthwhile to investigate this approach because it allows for mapping the interactions based on the actual data gathered and shared by vehicles. This may facilitate the development of interaction strategies that are able to maximize the impact on safety considering pedestrians and other vulnerable road users [8]. In analyzing the current interaction strategies evaluated in previous research, we focused on use cases that, although not classified according to the SAE J3216 taxonomy, fall into that group of cases catalogable as cooperation scenarios, operating a mapping based on the type of shared message and enabled interaction feature.

In Cooperation Class A (Status-Sharing), information is primarily used to increase the driver awareness. An example of this cooperation has been implemented in the research project SAFE STRIP [9], which developed a sensing and communication system to share data on safety-critical events (e.g., icy roads, wrong-way driving vehicles, etc.) with all vehicles in the local area that could be affected by that specific event. The HMI designed for this scope was intended to warn the drivers of a possible danger through an MQTT-based mobile app [10]. Other instances of this approach include the usage of OBUs as V2V communication access points, which allows the driver to be informed using information collected by other cars. An experimental example is provided in [11], where the goal was to develop a mobile HMI application to display real-time safety alerts and relevant information to the driver, including the host vehicle's speed, time to collision with remote vehicles, and the location of other connected vehicles relative to the host vehicle. Another study [12] used a similar approach to categorize HMI-related applications emerging from V2X-based ADAS systems. Furthermore, this research discusses the Integrative Warning Process (IWP) model based on the Communication-Human Information Processing (C-HIP) model [13], which describes human driver processing steps in reaction to received messages, analyzing concepts related to visual perception and strategies to guide the driver's attention to the specific area where the most relevant, dynamic information from ADAS based on V2X communication is conveyed. What emerges clearly from previous research is that status-sharing information is relevant for users in a traffic scenario only when it may lead to a safety-critical event.

While Class A allows monitoring of the current situation by extending the visibility and the perception of the driver, Class B (Intent-Sharing) also allows for the prediction of future events, such as the intention of the front vehicle to start an overtaking maneuver. This enables the driver to make decisions earlier in time and based on a more comprehensive understanding of traffic events. This principle is reflected in the possibility of increasing situational awareness towards the creation of a genuine “shared awareness” [14], i.e., a collective consciousness of the situation and the ability to make projections of the consequences of their actions [15] on the driving context. This is implemented through the definition of a transparency model [16] for human-robot interaction, also applicable to the vehicular context with awareness and intent as key objectives. Fostering shared intent can involve using the system's appearance, social cues, and communication style to convey its purpose and social orientation. Shared awareness can be supported by providing drivers with real-time information about the system's task progress, decision-making, environment, and collaborative role. As autonomy increases, it becomes critical for humans to understand the underlying logic and intent of automated systems, especially in safety-critical domains. Transparency methods can help establish appropriate trust, reliance, and coordination between humans and machines as partners. Examples of application of this model are represented by external HMIs (eHMIs), which are interfaces that allow communication with other road users, in particular with VRUs: they are usually made of visualization systems mounted outside the vehicle, e.g., light strips or external displays. These systems are used for a broad range of scenarios: in particular, they have proven to be effective in communicating the intention of automated vehicles to other road actors by replacing, for example, the mutual understanding given by the eye contact between drivers and pedestrians [17]. It is recognized that ambiguous implicit communication contributes significantly to pedestrian-vehicle collisions in current traffic, indicating that pedestrians might benefit from explicit eHMIs [18]. Furthermore, empirical evidence indicates that users are likely to use eHMIs as they might improve the effectiveness of pedestrian-automated vehicle interaction [19]. On the other hand, they might lead to negative effects such as distraction, confusion, and over-reliance. Dynamic external eHMIs might also impact on the user's gaze behavior in critical scenarios with additional traffic from the opposite side. Despite many design solutions that have been provided, there is no standardization in terms of methods and technologies for the visualization of eHMI features [18].

Solutions that can transform the driver's role from vehicle controller to decision-maker reflect a higher level of cooperation in HMI systems. In recent years, this trend has consolidated into the so-called ”negotiation-based approach”, first settled by Ju [20] at the conceptual level and then used in several automotive applications [21], [22], [23]. The negotiation-based interaction strategy can make use of the availability of information, as described by Class C cooperation (Agreement-Seeking), to provide tools to the driver for making decisions based on contextual information provided by the external environment. Systems based on this concept try to provide proactive explanations whenever possible, only generating warnings as a last resort. The interaction's major purpose is to provide evidence of the automated system's decision-making process and to assist the driver's decision by clearly stating the potential consequences of the action. In the ADS context, the driver and the vehicle may both make driving decisions, but there is no guarantee the driver will always agree or follow the system's decision as drivers can reject the system's proposal or regain control. When a conflict of decision happens, the vehicle can negotiate with the driver, similar to human-human communication, and the negotiation style needs to differ depending on the context of the conflict and the cause of the disagreement. As achieving appropriate driver trust is crucial to embracing the safety and comfort benefits of automation [24], research in this area has demonstrated that this approach can improve both automation trust and overall interaction effectiveness [25].

More complex cooperation techniques, such as those covered by Class D (Prescriptive Cooperation), can allow for different interaction strategies between the driver and the vehicle or between a system of vehicles. The extreme case of prescriptive cooperation, in which transportation authorities can direct traffic flows, further changes the driver's function. In a C-ADS context, the driver no longer has decision-making or vehicle control responsibilities and thus has no significant HMI requirements. However, other possible instances of prescriptive cooperation include scenarios such as platooning, i.e., the practice of coordinating groups of vehicles leveraging an assistance system called Cooperative Adaptive Cruise Control (C-ACC) [27]. This case is particularly relevant from the HMI point of view since the vehicle behavior, being entirely influenced by other external agents, requires explanations to increase the driver's awareness and trust. It is strongly recognized that platooning systems may be demanding and uncomfortable for drivers [28]. Nevertheless, the subject of platooning has been addressed with great emphasis from the V2V communication point of view but very little from the perspective of impact and adoption. Indeed, experimental research called attention to the need to develop usable interfaces that minimize distraction and maximize trust [29]. Although all these examples have incorporated innovative features in the way vehicles interact with the driver and the surrounding context, they have not fully exploited the cooperative model since they are not based on the systematic modeling of interaction strategies on cooperation classes, i.e., they are not based on how the vehicle and the environment "think".

IV. HMI for Cooperative Driving Automation

Given the rising complexity of traffic scenarios, this analysis highlighted the need to converge on common methodologies for designing HMI systems in the CDA setting. The primary challenges associated with interaction in this context encompass proficiently conveying the vehicle's condition, intentions, and perception of the surroundings to other road users, handling interference between the driver and automation, and fostering shared awareness and intent between humans and machines for safe and efficient interactions. Furthermore, major issues arise from dealing with drivers' expectations and behaviors resulting from their previous experience with manual driving, as well as their capacity to comprehend the information coming from other road users.

Because there is currently no standardization and many methodologies are used, in this work we attempt to draw some guidelines to support HMI design by including some best practices from recent research. Given that each cooperation class requires different tasks for the driver and different levels of cooperative and/or automated driving features, a preliminary set of recommendations for each cooperation class has been developed.

A. Status-sharing

HMI can play a primary role in conditioning the agents' response in DAS (L1-L2) devices, while it can serve to increase trust in automation in ADS (L3-L5) vehicles.

A1. *The HMI for the status-sharing cooperation class shall be alert-based, as the status of other cars shall only be sent to the ego-vehicle in the event of a hazard.* This recommendation is especially relevant for urban scenarios and situations involving vulnerable road users: in this case, the information provided to the different vehicles should be limited to safety-relevant situations because too much warning can overload the user with unnecessary information and reduce trust when the information is perceived as unnecessary, thereby reducing perceived reliance [30].

A2. *The HMI for systems based on the status-sharing class shall be designed to minimize reaction time by adopting a simple and clean design.* In fact, when the HMI is used to trigger an immediate reaction from the driver (as in most status-sharing cases), it is crucial to avoid unnecessary representations, such as complex animations, 3D, low-contrast graphics, etc. [31]

A3. *When possible, contextual information shall be visualized through tools able to avoid cognitive and visual distraction.* An example of this system are head-up displays, able to overlap the information to the driver's optimal visual (and therefore to the road) [32]. Recent research has also tried to introduce augmented and mixed reality elements in vehicle HMI systems [33].

B. Intent-sharing

B1. *The intent of other vehicles shall be shown trying to avoid ambiguous representations.* For example, in case of an intersection, the intent of another vehicle shall be displayed to a user, highlighting (i) the action required by the ego-vehicle (e.g., waiting for the other vehicle) and (ii) the intention/action performed by the other vehicle (e.g., entering the intersection). The first information is needed to suggest the action to the driver, while the second is used to explain the reason for the required action.

B2. *To show vehicles' intent, valuable solution can be eHMI.* As stated in the previous chapter, eHMI are a valuable system for communicating information in a distributed traffic scenario. An example of application of eHMI for this purpose is as an alternative to traffic lights [34] for personalized traffic scheduling.

B3. *eHMI shall avoid elements that may cause target users to doubt that they are the real recipients of the communication.* This is a typical problem and an open issue with eHMIs. Possible methods for implementing this recommendation include avoiding noise, flashing lights, atypical pictograms, and complex representations, instead using common color coding (e.g., red for 'stop; signals) and pushing for the standardization of eHMI solutions [35].

C. Agreement-seeking

C1. *The HMI for this cooperation class shall be focused on providing explanations to the user to increase situational awareness, creating "shared awareness".* As already stated, this recommendation is crucial to increasing trust and encouraging the adoption of automated systems. Explanatory systems have proven effective, particularly in non-critical situations [36].

C2. *The system shall recommend actions for successful cooperation and provide feedback about the success of maneuvers.* The recommendation shall be designed to persuade the driver of the appropriateness of the system's foreseen actions; the negotiation between the driver and vehicle, in fact, cannot be the same as a human-human negotiation, as they are not in equal positions [24].

C3. When the driver is required to provide input or feedback to the system, *natural interaction is preferable compared to other interaction modalities.* Natural interaction refers, for example, to pressing the accelerator to initiate a move (such as entering an intersection) and moving the steering wheel to initiate an overtake. These modalities have been found to perform much better than other interaction modalities, such as hitting buttons or using touchscreens [37].

D. Prescriptive cooperation

D1. When control is shared between the driver and the automation, *the system shall provide visibility of the current distribution of vehicle control tasks and clearly indicate the amount of authority that is dynamically in charge of the automation.* This is a crucial principle to increase situational awareness; this feature can be implemented, for instance, through dynamic sliding bars (indicating the level of authority) combined with textual/graphical labels indicating the automation mode to provide the driver with this information at a glance.

D2. *Provide continuous information on automation reliability for required driving tasks.* This principle is also related to trust, since it ensures that the driver does not disengage the automation, which has related impacts on safety.

D3. In cases of cooperative driving, such as platooning, *criteria and data regarding the relation to the lead vehicle shall be displayed to increase the transparency of the cooperation action.* While there is little research in this area, this guideline is intended to support users in understanding the mental model of automation, hence boosting trust and acceptance [38].

V. Conclusions

This paper presented a brief overview of current HMI design approaches in the context of Cooperative Automated Driving and proposed a set of recommendations for mapping design approaches to cooperation classes. These principles, which are based on empirical findings, shall be investigated in realistic settings to evaluate their effectiveness in terms of safety, traffic performance, and impact on users. Current HMI prototypes, in fact, are mostly tested in simulated or controlled environments, focusing the analysis on the effectiveness of the interaction strategy rather than the impact on the traffic environment. Additionally, their design is not built on cooperation classes; hence, they do not fully exploit information obtained in the traffic scenario. The next steps of this research include the development of a traffic monitoring and connectivity system in an urban environment that includes an HMI for connected vehicles, to test a prototype that incorporates these guidelines in a realistic setting.

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