Human Factors in the Design of Human-Machine Interaction: An Overview Emphasizing V2X Communication

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***Abstract*—More and more modern vehicles are incorporating connected technologies that use data collected by sensors located in other vehicles or infrastructure (V2X) to assist the driver. Deployment of upcoming technologies based on cooperative systems will likely be the key step towards a significant reduction of accidents across the globe. Particularly in the case of conveying information to the driver in the form of dynamic warnings based on V2X communication technologies representing different levels of danger, it is crucial to investigate driver distraction levels, as well as the modality and dimension of the visual warnings and their appropriate in-vehicle location. This paper summarizes and analyzes previously published works in the field of human machine interaction (HMI) for use in a vehicular context, in particular those which address messages conveyed by cooperative systems, providing the designer and the general audience with a background, variety of approaches and example applications of the most current and important concepts in the field.**

***Index Terms*—Vehicular user interfaces, in-vehicle displays, information visualization, human factors, cooperative systems, V2X**

I. Introduction

One of the most representative signs of our current society is the drastic increase in exposure to information made possible by the deployment of digital technologies that provide constant connectivity. This pervasive state of being connected allows the continuous exchange of information in a mobile environment. A key area to which digital technologies are applied is transportation, where wireless communications capabilities enable vehicular ad hoc networks (VANETs) in which the vehicles act as nodes that broadcast different data (e.g., for safety or entertainment purposes). This ubiquitous computing in an automotive context will improve the overall driving and traveling experience, for example by enabling access to traffic flow and road conditions data or by increasing the visual awareness of the driver after having processed information that stems from nearby driver behavior. It is expected that 75% of the estimated 92 million cars shipped globally in 2020 will be built with internet-connection hardware. This connectivity will entail new opportunities for suppliers, original equipment manufacturers (OEMs) and developers [1].

In 2013 the number of fatalities on European roads decreased to approximately 26,000 from 30,000 in 2011 [2]. At least some of this decrease may be attributable to technological advances that aim at supporting the driver, for example by alerting drivers of potentially dangerous situations. On the other hand, human error remains a leading cause of road accidents. Aggressive driving, intoxicated driving, drowsy driving, distracted driving, and expectancy violation are all forms of driver error that can degrade road safety. The human brain is limited and therefore not capable of performing several tasks at the same time with the same level of quality [3]. Thus, the growing number of information resources in the vehicle might decrease driver performance significantly by distracting them from the primary driving task or dividing the attention that, according to the definition in [4], is required to maintain longitudinal and lateral control within the traffic environment. Moreover, the fluency of communication between the user and the system is determined by the kind of information provided to the driver and the consequent navigation among the different graphical user interface (GUI) options [5]. Therefore, to ensure safety, the presentation of in-vehicle information should cause as little diversion from the primary task of driving as possible.

Connected vehicles will be able to compensate for a driver's weaknesses, sensing the surroundings and displaying information tailored to their preferences. In view of the increased awareness capabilities provided by the cooperative messages that rely on vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) (V2X, collectively) unique HMI systems are required to leverage this information that goes beyond the scope of non-connected systems and provide it to the driver in a very clear way [6]. Implementation of V2X communication-based HMI systems entails challenges that differ from those that need to integrate these communication capabilities. This includes the management of information and its presentation based on relative importance in a hierarchy through an integrative architecture that is able to manage multiple technologies and applications operating independently [7]. Connectivity technology will likely lead to broadcasting non-driving-related message types that compete with safety-critical information if they have not been ranked and discriminated appropriately.

This paper compounds and analyzes literature in the field of vehicular HMI, while emphasizing above all the design and in-vehicle presentation of V2X-based messages and how they affect driving performance. It serves as a guide for integrating the broad concepts of V2X and HMI design in specific ways in order to achieve safe and effective systems that adhere to

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current standards procedures. To this end, we address user interface design challenges that are uniquely associated with V2X technology. It is not the aim of this work to provide an exhaustive overview of all human factor guidelines for all possible in-vehicle systems, but rather to review basic groundwork for an understanding of some important human factors that influence the design and testing of these systems.

The following section provides a classification of V2X communication-based ADAS according to their function. Section III describes several V2X-communication-related works. Section IV describes the interaction design of ADAS based on V2X communication. The processes of perceiving visual stimuli are introduced in section V. Section VI provides the basic characteristics of warning messages together with conventional recommendations. Finally, Section VII concludes the paper.

II. Classification of V2X-based ADAS

V2X communication technologies integrated into ADAS increase vehicular environment perception. Safety and a decrease in traffic-related injury and death is the main objective of V2X technology. Some systems additionally focus on providing drivers and passengers with opportunities for a traffic flow improvement or useful and attractive in-vehicle user interfaces intended for entertainment. According to their tasks V2X communication-based ADAS can be categorized into the following 3 main groups: traffic efficiency, infotainment and road safety.

A. Traffic efficiency

Traffic efficiency applications are used for travel time, path or traffic light control optimization. For example, VANETs are used to dynamically optimize traffic flow by displaying traffic light information on the windshield as proposed in [8]. Other examples are V2X-based traffic light assistants which increase the efficiency of hybrid and electric vehicles [9] and optimized eco-departing operations to save fuel (in connected vehicles equipped with an internal combustion engine and a step-gear automatic transmission) by taking into account the acceleration of the leading vehicle to control the rear vehicles [10]. Further examples include applications that use algorithms that actively exchange messages between vehicles to set up platooning driving and ensure that the rate at which stopped vehicles at traffic lights begin driving is optimal [11] or for platooning control systems for electric vehicles [12].

B. Infotainment

Infotainment describes information applications that provide location-specific services such as content distribution, file sharing, streaming, mobile internet surfing, information on vehicle maintenance facilities, gas stations, toll collection, parking directions, tourist information, restaurants, shopping mall advertisements, etc. VANETs are used to disseminate service announcements and general interest messages [13]. Infotainment also describes entertainment applications such as in [14] where the authors highlight the benefits of multiplayer games for passengers that make use of an interactive and dynamic VANET environment, resulting in a practically free-of-charge experience for the end user.

TABLE I
V2X-BASED ADAS CLASSIFICATION

Functionality				
Traffic efficiency	Infotainment	Road safety		
Travel time, path or traffic light control optimization	Location-specific services	Reduction road fatalities and damage		
		Type messages [19]	Warning level [21]	Warning level [22]
		CAMs DENMs	One-stage (ICWs) Two-stage (ICWs + CCWs) Multistage (ICWs + CCWs)	Low-level Mid-level High-level

C. Road safety

Road safety applications such as cooperative ADAS (coADAS) based on V2X technologies seek to reduce road fatalities and damage through traffic condition warnings. Examples include intersection collision warnings or displays that augment the visual perception of the road in an overtaking maneuver [15], [16]. Cooperative systems may be divided based on levels of warning that they provide to the driver (imminent crash warnings (ICWs) and cautionary crash warnings (CCWs)) as summarized in Table I. In-vehicle warning messages will be further described in section VI.
Cooperative awareness messages (CAMs) [17] and decentralized environmental notification messages (DENMs) [18] are the two main types of safety messages that have been standardized by the European Telecommunications Standards Institute (ETSI [19]). Their main characteristics are summarized as follows [20]:

1) CAMs are periodically broadcasted by each vehicle to its neighbors to provide information about position, temperature and basic status. CAMs are delivered to vehicles in the immediate vicinity (located within a single hop distance). An illustrative use case for CAM-broadcasting is an approaching emergency vehicle (AEV).
2) DENMs are event-triggered messages transmitted to alert road users of a hazardous event. DENMs are delivered to vehicles in an area affected by the particular event periodically until the event is no longer occurring. Multi-hop transmission is used to reach farther nodes. AEV warnings, emergency electronic brake lights (EEBLs) and road condition warnings are typical representatives of DENMs.

III. V2X Communication-Related Works

A considerable amount of research has been performed in the field of V2X communication in recent years, a selection of which is presented here.

A. COOPERS

The European integrated project Cooperative Systems for Intelligent Road Safety (COOPERS) [23] focused on infrastructure-to-vehicle (I2V) communication systems. The project aimed at increasing road safety by broadcasting traffic information through communication technology located in the road infrastructure and motorized vehicles on a section of motorway. To this end, safety-critical warnings related to accidents, weather, roadwork, congestion, etc. were communicated and displayed to the driver. HMI-specific requirements were taken into account to develop the pertinent user interfaces and provide the best usability [24]. This affected, for example, the colors used to present the information and the size and location of the display(s). After rejecting other options, a 5 x 7 inch display with a resolution of 320 x 240 pixels was mounted on the dashboard in a lateral position. The authors decided on a maximum of five symbols to avoid cognitive overload of the driver. Critical and non-critical messages were discriminated by color, animation and sound cues. Besides a list of triggered warnings, a map-based view with plotted dangerous events was provided to drivers (Figure 1 [25]).

Fig. 1. Example of messages displayed to the driver within the COOPERS project [25].

B. COMPANION

Within the Cooperative Dynamic Formation of Platoons for Safe and Energy-Optimized Goods Transportation (COMPANION) European Commission project, the PlatoonPal platooning assistant was developed and evaluated in field test conditions with three platooning trucks [26]. The primary findings showed that the most important information for the test subjects was the one relevant to personal safety in terms of time and description of a certain event to be able to assess the level of safety. Furthermore, general functions should be held in the background but provide support in identifying important changes in the system (e.g. acoustic alert for finished merging action). In cases of danger, a warning alert or tactile cue were found useful to support drivers in perceiving the level of danger of the situation. Drivers said that they would like more detailed information about the exact next steps. For example, when merging, it would be useful to state that the speed will be increased, the gap is closed, that the truck is able to brake in any case.

C. SARTRE

Within the Safe Road Trains for the Environment (SARTRE) project, funded by the European Commission, strategies and technologies were developed to allow vehicle platoons to operate on normal public highways with significant environmental, safety and comfort benefits. The resulting platooning system, included a specific HMI that was evaluated in terms of user acceptance and perceived safety in a driving simulator [27]. Statistical differences regarding the perceived safety of the participants in the experiments were found depending on the number of vehicles involved in the platoon. Results showed that the participants felt confident and safe in the presence of a maximum of fifteen platooned vehicles in their driving environment.

D. SimTD

The "Sichere Intelligente Mobilität Testfeld Deutschland" (simTD) [28] project focused on V2X communication. More than 100 vehicles equipped with an on-board unit (OBU) exchanged data with each other, as well as with traffic lights, road signs, or the traffic control center. A variety of functions from different categories were tested, such as local danger alerts (obstacle warning, weather warning, congestion warning), driving assistance (EEBL, traffic rules violation, intersection assistance), traffic flow, and information and navigation (roadworks, advance route guidance). Regarding the interface, the chosen graphical representation was a color touch display with a symbol area in the upper corner. The main warning screen displayed a warning icon with distance bar and text labels (event and distance). Drivers were able to change the content of the main screen as they clicked on the symbols (virtual buttons), each of which had its own distance bar, so drivers knew which warning was most urgent at any given moment. Capacity of the symbol area was 6 warning icons (slots). The demand of interaction with the display was low, because the warning with the highest priority was automatically displayed on the main warning screen [29]. In case of imminent danger, the edges of the main warning screen turned red and a signal word was triggered in order to highlight the urgency of the situation.

E. Drive C2X

An additional project that tested the suitability of V2X technologies and HMI concepts in a real-life environment was the Car-to-X (C2X) communication project [30]. A portable tablet device was used to display a broad range of V2X messages ranging from traffic safety to infotainment. The information was distributed among two display sections. A map-based view was visible on the left side and a warning icon with distance bar and label on the right side. A speedometer was additionally displayed with a combination warning/information screen in the middle. Warning messages were transmitted solely through warning icons without additional text labels, and only one warning per screen was allowed. The urgency/severity coding was expressed via distance bar (map-based view) or color change (speedometer view) and warnings were accompanied by sound. The most important recommendations for improving the HMI gathered during the pilot tests were to increase the size of warning and informing icons and to remove the speedometer and distance bar [31].

F. SCORE@F

Similar to the Drive C2X and Co-Drive projects the "COopératif Routier Expérimental Français" project aimed at quantifying benefits of V2X, as well as developing different V2X applications. Thirteen use cases, most of them related to safety, were tested in order to prepare a large-scale Field Operational Test (FOT) before deployment [32]. Drivers behavior was recorded and post-questionnaires and interviews helped assess their acceptance of the system. In terms of HMI, a tablet was used within the tests, providing visual and audio feedback to the driver. A two-stage approach was chosen, such that ICWs and CCWs (if possible) were presented to drivers. The results revealed the diversity of opinions regarding the time, utility and frequency of the warnings displayed. It seems that they sometimes lost the ability to attract the driver's attention. However, all drivers were interested in being provided with information which was issued early enough and related to potential dangerous road situations [32]. In the system, the GUI was based on the map view with touchable elements on the right side. Warning messages, shown in a rectangle in the upper left corner of the screen, contained an icon specific to the scenario, as well as an event label, distance label with spatial and temporal proximity to hazard, signal word (in case of ICWs), and schematic road representation with hazard position (yellow dot) and position of ego vehicle. In order to highlight the urgency of a given dangerous situation, a red rectangle framed the warning message. Only one warning could be active (displayed) at any moment, and drivers were also given the capability to report a dangerous event themselves and announce it to drivers in a given direction.

G. INTELVIA

This project integrated technological solutions in the fields of computer vision, cooperative intelligent transportation systems (ITS) through wireless sensors/actuators, vehicular communications and intelligent HMI in order to enable intelligent traffic management with increased road safety and mobility [33]. Information concerning road signs and warnings (weather, roadworks, etc.) were wirelessly sent to a portable on-board device, the screen of which displayed the signs and warnings in a grid, which was divided into priority zones so that the driver could face multiple warnings at the same time. The high priority zone was devoted to the most urgent information. This information was transmitted to the driver solely via icon representation and urgency was coded via size of the symbol. Additional text labels could be displayed in the messages zone, used for various information, for example CCWs. Low priority signs and warnings appeared in the reminder zone, which was capable of visualizing up to three reminders (i.e. ICWs). Results showed that the information displayed was classified as easy to understand, clear, and user friendly.

H. Human factors for connected vehicles (HFCV)

Other key findings that addressed V2V and V2I HMI resulted from the HFCV multi-phased effort to validate a proof-of-concept of an integration architecture (IA) prototype designed to manage message presentation within a connected vehicle [7]. The participants were asked to assess the performance, message content and presentation of the system, including the ability to dismiss and filter messages. They additionally were asked about interaction modality preferences, and the results correlated partially with the findings in [34] where an international approach was followed. The participants were also requested to rate what type of information they thought was appropriate to receive while driving. The majority of participants were inclined to dismiss detailed messages if they were associated with speech information, suggesting that they were deemed of little use or presented for too long. Advertisement-related messages were blocked by the majority of the participants. They also emphasized the importance of personalized filters for non-interesting message types, the possibility of a relocation of high priority messages, and a display time reduction of additional messages. Vehicle-related information and warnings were rated as the most appropriate information to be displayed while driving, results that echo previous research in the field [35].

Summarizing the findings of the projects above, all of them tested user interface concepts based on graphical representations that contained several priority fields in diverse colors depending on the grade of urgency. In most of these cases, a user-friendly design fulfilled user expectations. The best rating for conveying information related to data exchanged with other vehicles or with road infrastructure was affected by whether this information related to potentially dangerous road situations (e.g., road accidents). Timed warnings with acoustic signals and visual representations of the distance to the hazards were rated with the highest score. Users rated positively messages that directly related to the vehicle or road situation and described them as useful and important. Other non-essential message content for drivers, like advertisements, created specific problems.

IV. Interaction Design of ADAS based on V2X communication

Driver response to systems developed to be operated in a vehicular environment can be influenced by the design of the warning message, the drivers mental state and experience (e.g., learned response patterns), and the current situation. For example, displayed warning messages in ADAS based on V2X communication should attract the driver's attention in a timely, suitable way, be clearly understandable for the driver and be accompanied with instructions via a combination of different visual, auditory or haptic modalities, all of which should lead to safer and more efficient driving. In automotive HMI design, capabilities and limitations of the driver should be included in the development of the final interface, using a model that best reflects their behavior in response to the particular environment. The Communication-Human Information Processing

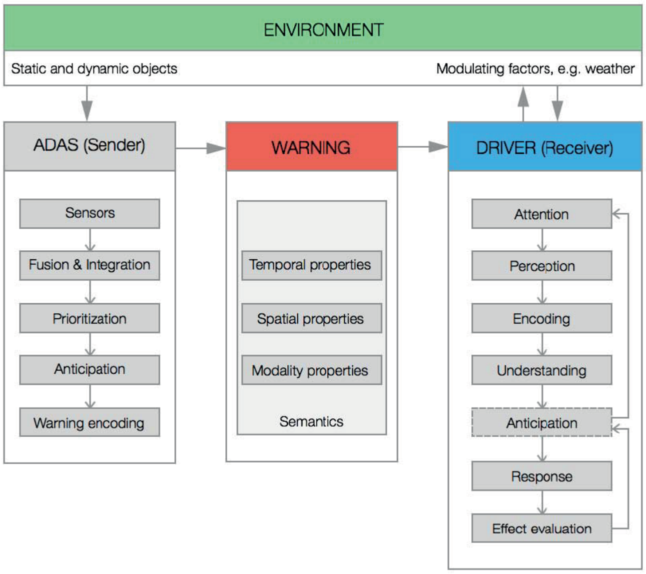

Fig. 2. IWP model based on the C-HIP model. Vehicular environmental information is compiled, assessed and forwarded to the driver by ADAS so that they are able to respond with adequate actions and modify driving behavior accordingly [38].

(C-HIP) model describes human (driver) processing steps in reaction to received messages. It includes subjective factors like attitudes, beliefs, and motivations, which ultimately shape the behavior of driver [36], [37]. An Integrative Warning Process (IWP) model based on the C-HIP model was presented in [38] and is shown in Figure 2. Relying on the definition of Communication model, using the concepts of information source, message, transmitter, noise, information destination, encoding, decoding, receiver, etc. [39], the IWP model describes a situation in which the driver is moving through a vehicular environment that is characterized by specific conditions (e.g., highway with wet surface, traffic congestion, etc.). The driver is supposed to change their behavior in relation to the current situation while maintaining vehicle safety. The environment is sensed and evaluated by ADAS (sender), which sends a warning with specific properties to the driver (receiver) (e.g., "slow speed", "slippery road"). The driver evaluates the environment and together with information from ADAS, situational awareness in the vicinity is gained. Then, the driver is able to respond with an adequate action and modify behavior accordingly. This kind of feedback loop between the driver, ADAS, and the environment creates dynamic interaction which is characteristic for driving. ADAS is capable of quantifying and prioritizing particular hazards by predefined criteria (e.g., proximity and/or severity). They are then decoded into warning messages and forwarded to the driver.

To further understand the driver it is necessary to incorporate the Human Information Processing (HIP) model [40], which views driver behavior as highly influenced by interaction with the environment and a human-made system. Human performance levels are associated with driving task levels and organized in a hierarchical way. Figure 3 depicts the processes [38]. The driver can be considered as a control

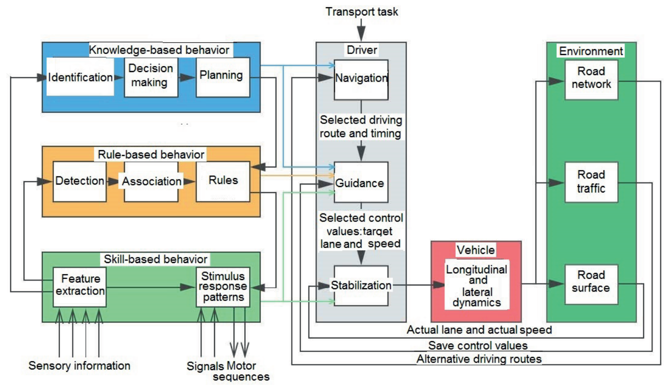

Fig. 3. Wieners complex processing model representing the human performance levels associated with driving task in a hierarchical way (adapted from [38], published in [44].

feedback system and the resulting behavior can be described by Rasmussens Performance model [41] and the Control Hierarchy model [42] comprising three levels [43]: a stabilization task that requires the least attentional resources and includes driver actions for the physical operation of a vehicle (e.g. keeping in the lane by steering); a guidance task or interacting with other vehicles (e.g. following, overtaking, merging); and a navigation task in which the driver chooses a route from origin to destination by using landmarks and by performing related actions. Navigation is the task that demands the most attentional resources.

V. Visual Awareness

In this section we explain 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. Driver glance behavior is clearly correlated with visual perception and related visual processing steps. It is characterized by eye movements that are applied while driving and elicited when measuring interaction with a graphical interface of ADAS. Experiments performed in controlled environments, such as driving simulators, in which the eyes-off-road time was evaluated as parameter to investigate visual attention confirmed a time window between 1.6 [45] and 2 seconds [46] as safe, showing that a longer time was the major cause of more than 23% crashes and near-crashes [47]. As previously mentioned, ADAS warning messages should attract the driver's attention in a timely, understandable way and be accompanied with instructions. This can be achieved by using object, urgency and direction cues that in an anticipation stage will elicit a response from the driver.

A. Object, urgency and direction cues and non-conventional placement of V2X warnings

Object cues are representations of elements of an event (e.g., a line of vehicles to represent congestion), or objects associated with an activity (e.g., a brake pedal to represent immediate braking) [48] and may help the driver to understand a warnings cause and anticipate consequences.

Fig. 4. Object cue in combination with direction cue that warns a VRU about a vehicle in the immediate vicinity, and states the position of the danger [51].

Urgency cues alert and assist the driver in noticing warnings and may also modify the intensity of the driver's response. As examples one can consider a sound signal with different intensities depending on the severity and/or urgency of a hazardous situation, haptic feedback from the steering wheel or vibrations incorporated in the vehicle, as described in [49]. Auditory and haptic warnings without a visual confirmation of the threat can also impact driver behavior in the case of potential hazards that take place outside the driver's field-of-view.

Direction cues such as LED lights within the vehicle or arrows (see Figure 4) direct the driver's attention to a hazard or relevant location and thereby facilitate perception and action [38]. The efficacy of these cues may decrease in HMI that provide a large quantity of messages based on V2X-related information. Still relying on these basic cues while expanding the range of possible display areas non-conventional locations could provide benefits in HMI for connected vehicles, especially if these locations provide more effective ways to convey important safety-related information. To illustrate this idea, we describe the following scenario relying on a cooperative system to promote the observance of the safety distance between two vehicles [50]. The driver follows a leading vehicle which starts to brake suddenly. The system garners information through the stereoscopic capturing and processing of images by cameras. Visual warnings related to safety are provided to the rear vehicle in real-time in form of a color-coded urgency cue with a command message (Figure 5). An object cue depicts additional information regarding the distance from the leading to the following vehicle to increase the driver's visual awareness of safety distance to, for example, perform an overtaking maneuver.

Because human beings are capable of processing only a limited quantity of stimuli in both space and time, attention is the dynamic process whereby we select some stimuli for further processing (those which are relevant to our goals) while we inhibit the processing of others [52]. Attention encompasses at least three aspects: orienting, filtering and searching, and can either be focused on a single information source or divided among several (divided attention) [53].

B. Endogenous and exogenous cues

1) Orienting: Orienting implies the process in which one focuses sensory receptors toward one set of stimuli and away from another. One is also able to orient attention without

Fig. 5. Urgency cue related to safety distance provided to the rear vehicle in real-time [50].

physical movement of the eyes, for instance, when one is driving a car with eyes on the road while thinking about work responsibilities. One can redirect attention to an object or event voluntarily, based on knowledge and goals. This goal-driven attention orientation is said to be endogenous, and stimuli which trigger it are endogenous cues (e.g., visual symbols, voice commands) [54]. Endogenous cues usually guide one as they take certain expected steps toward completing a task in a non-critical situation, and therefore these cues only make sense in the context of the task. In the study in [55] endogenous cues in the form of arrows pointing to a possible target location were used. Results showed that this alignment of attention enhances processing of the event significantly.

Contrastingly, attention can be oriented using exogenous cues [56] in critical situations (warnings). These exogenous cues are pronounced and powerful stimuli, e.g. a bright light in the peripheral field of vision or an intense sound signal [55]. They do not require complex contextual information to be understood, and they are not part of a series of tasks to achieve a predetermined goal. An exogenous cue can be located away from the center of gaze, but still within the visual angle.

2) Filtering: Filtering is another aspect of attention whereby unattended stimuli are filtered out while further information is extracted from attended stimuli [57]. The process is influenced by an individual's mental state (workload, fatigue, experience, effects of drugs, mood, etc.) and the difficulty of the task to be performed (a navigation task is more demanding than a stabilization task, multiple concurrent tasks require more cognitive resources than a single task, etc.) [58].

3) Searching: Because visual-based warning messages divide the driver's visual attention, a visual ADAS interface needs to be as intelligible as possible in order to minimize the need for excessive stimuli extraction. A visual search task in the driving context is based primarily on endogenous orienting, i.e. drivers detect target areas related to their goals and direct their attention to the most critical information displayed in the GUI. To ensure driver ease in this task, these target areas should have different characteristics than other stimuli on the display. Even an increased number of presented stimuli (i.e., increased search set) does not slow down target detection if the target holds a unique characteristic (e.g., color). Conversely, a conjunction of characteristics (e.g., color, shape and orientation) among stimuli prolongs the time it takes to distinguish a target [56]. A conjunction of simple characteristics sometimes also leads to a rapid search [59]. In section II it was stated that V2X applications can be categorized into 3 main groups according to their functionality: traffic efficiency, infotainment and road safety. Certainly, the safety-related applications have to be prioritized over the other groups, and there must also exist a visual hierarchy among safety applications (e.g., based on the proximity to the hazard) in order to facilitate the driver's visual search. GUIs used in the vehicle should therefore rely on cueing principles to guide the driver's attention to the most relevant information on the in-vehicle display and subsequently orient their attention to the specific area in the environment.

VI. Considerations for Design of co-ADAS Warnings Messages

In-vehicle warning messages are a core feature of V2X applications. They will therefore serve as a prime example of how to best integrate all of the human factor concepts and metrics from the previous sections into the design of the HMI. We will now look at some of the specific considerations for warning messages such as modality and dimension of warnings, including their use, in-vehicle location, color, use of icons and text, as well as the prioritization of warning messages. As observed by [60] after having performed experiments on message coding, three general categories of events resulted: "high threat", "caution" and "no action required", depending on whether an immediate driver response was required or more informational messages did not require urgency or action. Moreover, there was a strong relationship between the perceived level of urgency in a scenario and the means of conveying priority according to the three levels of urgency. The analysis suggested that more effective responses for the most urgent messages resulted when they interrupted and revoked all other messages.

The following sections provide the basic characteristics of visual warning messages together with conventional recommendations.

A. Warning stages

As shown in Table I warning systems can be distinguished depending on the number of stages that they involve [21]: one-stage warning systems, two-stage warning systems and multi-stage warning systems.

1) One-stage warning systems provide drivers with information related to ICWs that require an immediate corrective action within 2 seconds.
2) Two-stage warning systems broadcast ICWs and other CCWs warnings. This two-stage warning system requires corrective action within a time period of 2 to 10 seconds to avoid the upgrade of a CCW to an ICW.
3) Finally, multistage warning systems are based on a continuous warning strategy that consists of informing the driver on a regular basis about the state of danger. For instance, a five-stage system may comprise levels such as: 1) no vehicle detected, 2) vehicle detected, 3) caution, 4) vehicle approaching and 5) imminent crash.

Warnings can also be classified into a specific sequence of events potentially leading to an accident and there are certain countermeasures that can be applied in all stages. The only exception is the last stage, in which passive systems can be used to mitigate the consequences of the crash. As the situation escalates from an emerging stage to a critical one, according to [22] the following levels of warning can be distinguished:

1) Low-level warnings correspond to the situation where the driver has sufficient time (around 10 seconds to 2 minutes) to prepare for an announced event or threat. If the driver does not take any action a higher level warning may result.
2) Mid-level warnings require the driver's reaction within a smaller time-frame, around 2 to 10 seconds. A failure to react appropriately may progress the situation to a higher level warning stage.
3) High-level warnings occur in the most urgent situations when the driver has only minimal time to take action for an announced threat. Since the time required to initiate the appropriate response is less than 5 seconds (usually even less than 2 seconds), these warnings may include an action recommendation, so as to speed up the driver's response. Sometimes such warnings are accompanied by automatic intervention from ADAS (e.g., by automatic braking), which represents the best option in terms of driver's safety. A gradual transition between these levels is not a condition, and thus a high-level warning may occur without preceding levels.

B. Modality and dimension of warnings

Information and warning messages can be transmitted to drivers via different modalities or via their combinations. The three main groups of modalities we distinguish are visual, auditory, and haptic, each of which having its own advantages and disadvantages which restrict its usage in different driving situations. The choice of modality depends on the users' familiarity with its use and significantly affects the driver's processing steps. Therefore, it should be carefully considered. For example, the authors in [60] investigated these three warning modalities and found out that professional drivers felt that the combination of modalities for forward collision and lane change warning was appropriate for use in commercial motor vehicles. However, they had generally negative reactions to using a haptic modality for warning presentation. In the study it was not clear to what extent the differences observed in driver response were related to the inherent features of the devices, or to the warning and messaging strategies.

1) Use of visual, haptic and auditory warnings: Visual warning messages may be quite dangerous because they require saccadic movement of the driver's eyes and can lead to too-long eye fixations during a critical driving situation. Visual warnings are not omnidirectional and may not be seen, not even peripherally, if the driver is looking in a different direction from the display unit (center stack, mirror, etc.). Therefore, visual high-priority warnings should always be combined with at least one additional warning modality element (auditory and/or haptic). Due to the possibility of a hazardous division of attention, some HMI guidelines (e.g., [61]) even recommend suspending all visual warnings in the event of an imminent crash situation and applying only auditory and haptic cues for ICWs themselves. As stated in [49], a tendency has been observed to visually assess the situation after receiving a tactile warning to which the driver needs to respond [62]. However, tactile stimuli located, for example, in vibrating eyeglasses, seats or body parts resulted in faster reaction times than visual or auditory ones [63], [64]. Depending on the main goal of the V2X application, results regarding simultaneous visual information conveyed to the driver can vary. The authors in [60], [65] studied the effect of being informed by several displays on driver response to ICWs. Results showed that the warnings were recognized faster when only one display was active and that color coding was helpful. In addition, they found out that the driver interface should provide an intuitively meaningful indication of the presence of a warning, or an assist function in the vehicle showing its current status. Descriptive terms and clearly labeled function buttons, icons or even full words were preferable to hierarchical menu structures, acronyms being found ineffective.

2) In-vehicle location of visual warnings: According to the study on reaction times by [66], different display locations in the vehicle cause a different level of distraction, and frequently used displays should not be located in the center console. Moreover, the closer the display was positioned to the windshield (e.g., above the mid-console or dashboard), the more favorable the effect on driving performance, due to reduced visual demand [67], [68]. According to this, preferences for the layout and location of functions from infotainment, ADAS and smart phones connected to in-vehicle systems were analyzed and validated through driver performance and gaze location metrics in [69]. The study showed that drivers preferred having entertainment-related functions displayed outside the driver's visual field. Figure 6 depicts possible in-vehicle visual areas for warning and information. Participants preferred ADAS and systems that alert the driver about potentially unsafe situations to be presented on displays 1 or 3. Entertainment, communication and office-related functions not directly related to the vehicle or road situation were preferred to be visualized on display 5. Functions related to vehicle status and indicators were mainly preferred to be shown on display 2. "Climate" and "CD player" clearly indicated a preference for center console location. Results related to social media integration and mobile applications in an in-vehicle context showed that these functions were not relevant for driving. Only internet connection was selected as important to be displayed in the vehicle.

3) Visual warnings colors and icons: Effective use of color can help drivers to group and code information, attract driver attention more quickly, and facilitate the interpretation of information particularly for different levels of warning. For the correct representation of colors cultural adaptation needs to be considered in an ergonomic design, in order to reduce technology-based distraction in a vehicular context [71]. For most populations in western, red is associated with danger, amber or yellow is associated with caution, and green is associated with a problem-free state. Based on these assumptions, the color red should be used for high-priority warnings demanding immediate action from the driver (e.g., ICWs), amber or yellow should be used for less critical warnings (e.g., CCWs), and green should connote incident-free conditions or successfully executed actions (i.e. should not be used for warnings at all). If high-priority warnings are displayed near the instrument panel indicators, the use of the color red is not suitable, as some indicators (e.g., seat belt indicator) already use the same color and the possibility exists that a high-priority warning could be easily confused with a non-critical indicator [72]. It has been suggested that for low-level warnings the color blue may be used [73]. However, colors alone are not enough for conveying a warning message and should always be paired with other information means (e.g., text label, icon) in order to ensure a certain level of situational awareness.

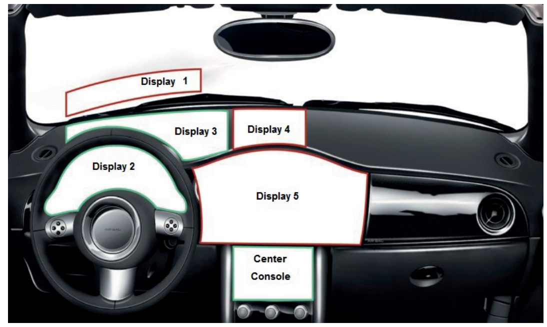

Fig. 6. Possible in-vehicle visual areas for the location of warning and information messages. Published in [69] (adapted from [70]).

Icons are simple, minimalistic graphical representations used to symbolize an object, action, situation, status, or idea. The condensed information that they present, makes them well-suited to represent safety-related messages, thereby significantly speeding up drivers processing steps in comparison to text-only representations. In some instances, an icon alone is insufficient for conveying its meaning, and supplemental text (label) is necessary.

4) Visual text messages: Text labels and signal words provide complementary information about the nature of warnings. Signal words are a special category of text label situated on or near an icon, whose main goal is to capture the driver's attention and stress the relative urgency of a presented message. A text label should preferably be placed either at the bottom or top of the icon, although occasionally text labels can be placed directly on the icon itself, given that the legibility of the icon/shape is retained [74]. Typeface and its readability are key for both driver satisfaction and safety. Recently, a study on legibility of typefaces on screens under glance-like conditions revealed that a humanist (Frutiger) typeface could be read accurately in shorter (8.8%) exposure times than a square grotesque (Eurostile) typeface [75]. Message length is another basic feature of a visual text message. According to [76] a message's content is expressed through so-called information units and usually contains two, four, six, or eight units. The number of information units has an inverse relationship with the priority value, so that for high-priority messages no more than two information units are used (e.g., "crash ahead"). These messages are both urgent and critical, and thus one should minimize attentional demands caused by their reading. Another factor influencing number of information units is driver workload. As shown in [7] drivers tend to access more information when workload is low (e.g. in a traffic light stop), while ignoring messages in a demanding traffic situation with high workload (e.g. overtaking). No more than four information units should be used while the vehicle is moving.

Messages that directly command drivers to perform certain actions in reaction to the environment (e.g., "slow down", "keep distance" (Figure 5)) suggest a specific action to be taken in order to prevent a dangerous situation. Their purpose is to elicit an immediate response without initial processing steps (see driver processing steps in Figure 2). They are most appropriate for conditions of high stress and time pressure [40]. This fact implies the use of command messages in the event of high-level warnings. An additional study confirmed this statement, as it revealed that command messages lead to a 20% better warning compliance and as one could expect, lower mental effort in comparison to notification messages. On the other hand the study also found out that trust in the system and the self-confidence of drivers was higher for notification messages [77].

C. Prioritization of warnings

Warnings are always associated with particular events in the environment. When multiple events occur at once in the environment, some may have more serious consequences for the driver than others, and the time to react to these events is different. Therefore, warning messages from ADAS shall always be superior to messages from other in-vehicle systems (e.g., infotainment system). Moreover, ADAS messages related to comfortable and efficient driving should also be suppressed in the event of an ADAS warning message until the threat desists. In line with this, the authors in [60] investigated whether a driver's response to multiple individual warnings from collision avoidance systems differed from the response to a unique alert, this work providing insight into methods for securing more adequate responses and identifying subjective preferences for multiple warnings.

The standardized priority index method in [78] can be used to prioritize ADAS warning messages. This method comprises several steps which can be summarized as follows:

1) Preparation of messages: In this first phase, it is necessary to identify the group of messages to be prioritized and create an evaluation list. Every message is characterized by a specific driving scenario including context and conditions (trip type, roadway type, speed, weather, traffic situation, vehicle type, vehicle condition).
2) Selection of global critical and urgent coefficients: Next, the critical coefficient k_c and urgent coefficient k_u for the entire evaluation list is selected to determine the weight of urgency and criticality.
3) Selection of local critical and urgent coefficients: Each message i receives a certain urgent coefficient u_i and critical coefficient c_i. Values of these coefficients are based on a four-point scale (0-3), as shown in Table II and Table III, and reflect the urgency and criticality of a given situation, i.e. possible risk to the vehicle, occupants, and/or pedestrians, and/or environment respectively.
4) Prioritization among messages: Each message receives a resulting priority value p_i based on the following equation:

$$p_i = k_c c_i + k_u u_i$$

Based on the final priority value, a final list of warning messages can be derived that is sorted from highest to lowest priority. When messages have the same priority value, the message with the highest criticality score should have the higher priority. In the case of simultaneous high-level ICWs, the presentation of lower priority warnings is suppressed until the higher priority hazard ceases.

TABLE II
RELATIONSHIP BETWEEN THE URGENT COEFFICIENT AND REQUIRED RESPONSE BY THE DRIVER (ADAPTED FROM [78])

Urgent coefficient	Action required
$u_i = 0$	Information only; no direct action required by driver.
$u_i = 1$	Response preparation needed; action needed between 10-120 seconds.
$u_i = 2$	Response required within 3-10 seconds.
$u_i = 3$	Imminent response required (0-3 seconds).

TABLE III
RELATIONSHIP BETWEEN THE CRITICAL COEFFICIENT AND CONSEQUENT INJURY OR DAMAGE (ADAPTED FROM [78])

Critical coefficient	Injury or damage
$c_i = 0$	No injury, vehicle/environment damage.
$c_i = 1$	No injury or damage.
$c_i = 2$	Injury or possible injury.
$c_i = 3$	Severe injury or fatal injury.

VII. CONCLUSION AND FUTURE WORK

This article provides insight on how to enable safe interaction with co-ADAS based on V2X technologies and gives a brief overview of the complexities related to the design and adaptation of in-vehicle systems that ensure road safety and usability. Different aspects (e.g., information architecture, graphic elements, etc.) of V2X HMI have been reviewed that have been part of research in previous studies. Although not exhaustive in its content, it presents their main implications for HMI as summarized below.

- Safety-related in-vehicle systems, such as ADAS, can deviate attention from the primary task of driving and overload drivers. Therefore, when assessing an in-vehicle system, it is mandatory to verify the level of distraction and workload it causes.
- In order to ensure situational awareness, ADAS and systems that alert the driver about potentially unsafe situations should be presented in the driver's visual field to attract their attention in a well-timed way, via a combination of clear visual, auditory or haptic modalities.
- Infotainment messages however, should be displayed outside the drivers field-of-view.

- The driver interface should provide an intuitively meaningful indication of the presence of a warning and its current status.
- Warnings conveyed from simultaneous visual information should be displayed only on one physical location.
- The use of command messages in the event of high-level warnings in conditions of high stress and time pressure is recommended.
- Color coding should be used to ensure a rapid visual search task in critical elements in a display.
- Descriptive terms and clearly labeled function buttons, icons and words should replace hierarchical menu structures.
- Filters to prioritize messages and interesting information should be available.
- The perceived level of urgency of messages depends on the scenarios and the means of conveying priority. Multiple output modalities need to be consistent with the urgency level conveyed.

HMI systems based on cooperative V2X messages provide information beyond the scope of today's complex HMIs that do not have V2X communication capabilities. Therefore it is imperative to organize these messages according to their critical or informative nature, taking into account warning stages, modality and dimension as well as their prioritization in a proper location in the vehicle. The very likely use of V2X by providers as an avenue for creating advertising and other non-essential message content for drivers can create very specific problems and therefore it could be a need to strictly limit the use of HMI for these uses, or for the creation of very distinct visualization paradigms between safety-related V2X messages and other messages. Therefore, systems should provide options for the users to modify the configuration for the duration and prioritization of messages. Further placements to show information conveyed by vehicles in the proximity should be addressed in future research focusing on challenges related to driver response regarding new message visualization paradigms [79].

Limitations of previous work showed that differences observed in driver response to several warning modalities could not be derived from inherent features of the devices or from the warning and messaging strategies [60]. Even without scientific consensus on which modality is the most effective to attract driver attention, low-level warnings especially could benefit from haptic feedback. This could reduce the startling effect from sound cues and simultaneously complement non-omnidirectional visual warnings. Therefore, these aspects need to be studied in future research as well.

Most of the research so far has been implemented in simulation platforms. Real world implementation and evaluation of connected technologies in a vehicular environment needs to be performed [7]. Studies of Dedicated Short Range Communications (DSRC)-based connected vehicle safety applications that focus on real-world driving scenarios in a multimodal operating environment are needed to assess distraction and crash reduction, as well user acceptance of connected vehicle technology [80]. Systems that are intended to assist in platooning need to detect and represent the vehicles on the road that belong to the specific platoon. This is critical to make sure that drivers can anticipate how the system will react to a vehicle that enters the platoon. Further research is needed to find out the best method of identifying new entering vehicles. Examples could include marking trucks with external lights or displaying an image of a bird's-eye view of the traffic scene that highlights relevant vehicles [26].

Further study involving in-vehicle warnings about the presence in the roadway of vulnerable road users (VRUs), such as pedestrians and bicyclists, and the transfer of information to the VRU though mobile devices is also necessary [81], [51].

In the case of automation in vehicles, interfaces should also display information about certain system actions that users can simply confirm for themselves to help them build trust in the connected system, proving that they can rely on it. This field is therefore also important for further research.

Other items that should be further investigated include improving a system's management of information according to the current driver's workload or distraction level [82]. In this context a specific issue surrounding V2X messages that can be further investigated is the impact of secondary tasks on the driver performance after a distraction phase has been completed, as suggested in [83].

Summarizing, to effectively design systems consistent with user expectations, more research is needed on driver perception, identifying safety attributes for the driver's mental model [60].

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