THE USABILITY OF GRAPHICAL SYMBOLS AND VISUAL AIDS DESIGNED FOR DRIVING AUTOMATION SYSTEMS

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Submitted in accordance with the requirements for the degree of

Doctor of Philosophy

The University of Leeds
Institute for Transport Studies

2022

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The 1st work, in Chapter 2 of the thesis, has appeared in publication as an 'extended abstract' as follows:

Perrier, M.J.R., Louw, T.L., Gonçalves, R.C., And Carsten, O.M.J. (2019). Applying participatory design to symbols for SAE level 2 automated driving systems. In *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications: Adjunct Proceedings (AutomotiveUI '19)*, 238–242. DOI:10.1145/3349263.3351512.

The candidate contributed substantially to the conception and design of the study. The candidate collected, analysed, and interpreted the data, and wrote the article. TL and OC provided contributions to the conception and design of the study and reviewed the manuscript. RG provided support during the data collection.

The 2nd work, in Chapter 3 of the thesis, has appeared in publication as follows:

Perrier, M.J.R., Louw, T.L. & Carsten, O.M.J. (2021). User-centred design evaluation of symbols for adaptive cruise control (ACC) and lane-keeping assistance (LKA). *Cognition, Technology, and Work*, 23, 685–703. DOI:10.1007/s10111-021-00673-0.

The candidate contributed substantially to the conception and design of the study. The candidate collected, analysed, and interpreted the data, and wrote the article. TL and OC provided contributions to the conception and design of the study and reviewed the manuscript.

The 3rd work, in Chapter 4 of the thesis, has appeared in publication as follows:

Perrier, M.J.R., Louw, T.L. & Carsten, O.M.J. (2022). Usability testing of three visual HMIs for assisted driving: How design impacts driver distraction and mental models. *Ergonomics*. DOI:10.1080/00140139.2022.2136766.

The candidate contributed substantially to the conception and design of the study. The candidate collected, analysed, and interpreted the data, and wrote the article. TL and OC provided contributions to the conception and design of the study and reviewed the manuscript.

The 4th and final work, in Chapter 5 of the thesis, has been submitted for publication as follows:

Perrier, M.J.R., Jamson, S.L., Louw, T.L. & Carsten, O.M.J. (Under Review). "What's doing what?" A usability comparison of 'affording' and standard ADAS symbols for SAE L1 to L3 ADS vehicles in a driving simulator. Submitted to *Theoretical Issues in Ergonomics Science*.

The candidate contributed substantially to the conception and design of the study. The candidate collected, analysed, and interpreted the data, and wrote the article. TL and OC provided contributions to the conception and design of the study. SJ and OC contributed to the interpretation of the data. SJ, TL, and OC reviewed the manuscript.

Acknowledgements

I would like to thank:

My supervisory team—past and present—in order of appearance: **Oliver Carsten**, **Daryl Hibberd**, **Tyron Louw**, and **Samantha Jamson**. I have thanked them many times before, but this is the ultimate “Thank you for your time and your comments” of them all. Thank you for your Marathonian support and your inexhaustible patience in dealing with my French-English neologisms (among other things).

The team at the University of Leeds Driving Simulator, especially **Michael Daly Anthony Horrobin**, and **Andrew Tomlinson** without who I would not have had much to tell! Thank you for your long hours of coding and debugging to make these two driving simulator studies a ‘simulation’.

The Human Factors and Safety research group and its members, especially **Natasha Merat** for bringing everyone together on so many occasions. I am sure these moments will remain in everyone’s memories forever.

The Super Tram cover band core members, **Daniel Johnson** and **Bryan Matthews**, without who I would not have had the chance to play a Muse song at UTSG 2019, in The Refectory of the Leeds University Union, 18 years, 1 month, and 14 days after the band had performed on the very same stage!

The people I have met from all around the world and who contributed to making the years 2018-2021 an unforgivable period of my life, especially **Alberto**, **Chiara**, **Cristhian**, **Davide**, **Evangelos**, **Giovanna**, **Haruko**, **Jean-Christophe**, **Julio**, **Lamprini**, **Lena**, **Morayma**, **Natalia**, **Natan**, **Romain**, **Thalia**, **Vishnu**, **Rodrigo**, but also all the other ones.

Et enfin, je voudrais remercier **mes parents**, qui n’ont jamais bien compris ce que je faisais mais qui m’ont toujours tout de même soutenu.

Special mention to anyone reading this dissertation, partially or fully.

Abstract

Inconsistencies can be observed in the way vehicles equipped with driving automation features will inform drivers about a particular system's state or capabilities and limitations: different graphical symbols are used across manufacturers to represent the same feature, while other graphical elements presented on the instrument panel can also differ in their designs. This situation could engender confusion among drivers, while some designs may be less informative and/or less usable than others, eventually being detrimental to driver safety. The objective throughout this project, therefore, was to demonstrate whether symbol confusion was an actual risk and whether the different symbol and interface designs could have measurable consequences on a vehicle's usability. Ultimately, the goal was to determine which methodological approach could help design symbols and interface elements that would prevent or mitigate these putative consequences.

Firstly, two studies were conducted with a user-centred design (UCD) and participatory design approach to ① investigate drivers' mental models of the adaptive cruise control (ACC) and lane centring control (LCC) systems and design symbols for these two systems, and then, to ② research which symbols would be the most recognised by drivers contextually and alongside other symbols present in vehicles. Secondly, two driving simulator studies were conducted to ③ compare the usability of different graphical elements shown on the instrument panel for ACC, including different designs of the same symbol, and finally, ④ compare two sets of symbols for ACC, LCC, lane departure prevention (LDP), and the automated lane-keeping system (ALKS), in terms of driver preference, but also on how much confusion and how many errors would occur while drivers were using either set.

Overall, the results suggest that some existing symbols (notably the standard ones) lack information about which actions are automated by a system, or how the visual representation of the environment relates to the actions performed by the system. In scientific jargon, drivers overall preferred, recognised, and committed fewer errors with symbols that depicted drivers' affordances and the signifiers that the vehicle was using in place of the driver. Through this project, it was observed that: indeed, symbols can confuse drivers and contribute to use errors of the automated driving features; that interface designs could impact the usability of vehicles differently; and finally, that a combination of UCD and participatory design can help design better symbols. In the case of symbols for driving automation systems, designers should consider the context of use of the system and which affordances/signifiers should be represented on the symbol.

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List of Abbreviations

ACC	Adaptive Cruise Control
ADAS	Advanced Driving Assistance System
ADS	Automated Driving System
ALKS	Automated Lane Keeping System
CC	Cruise Control
CI	Confidence Interval
COVID-19	Coronavirus Disease 2019
DVI	Driver-Vehicle Interface
FCW	Forward Collision Warning
FHWA	Federal Highway Administration
HMI	Human-Machine Interface
IRR	Incidence Rate Ratio
ISO	International Standardization Organization
LCA	Lane Centring Assist
LCC	Lane Centring Control
LDP	Lane Departure Prevention
LDW	Lane Departure Warning
LKA	Lane Keeping Assistance
LKS	Lane Keeping Systems
ODD	Operational Design Domain
OEM	Original Equipment Manufacturer
OR	Odd Ratio
RSME	Rating Scale of Mental Effort
RT	Response Time
R-TLX	Raw Task Load Index
SAE	Society of Automotive Engineering
SE	Standard Error
SUS	System Usability Scale
TGT	Total Glance Time
UCD	User-Centred Design
UI	User Interface
UNECE	United Nations Economic Commission for Europe
UX	User Experience

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Chapter I
General Introduction

I. Research Context

While flying cars have not become Humans' predilected transport means at the dawn of the third millennium—like many people were fantasising about—the development of driving automation on the other hand has known an accelerating growth over the past decades. Automation went from relieving drivers of pressing the throttle pedal in 1958 with cruise control* (CC), to also relieving drivers of decelerating or braking their vehicle in response to other road users with adaptive cruise control (ACC) in 1999, to then allowing drivers to take their hands off the steering wheel in 2017 with Cadillac's version of lane centring control (LCC), manoeuvring their cars on US highways, to then finally taking the charge off of drivers of even attending the driving task under certain conditions with the automated lane-keeping system (ALKS) in 2022. Yet, the general public is still rather uninformed or misinformed about these technologies, their operation, and their limits (e.g., DeGuzman & Donmez, 2021; Greenwood et al., 2022; Kaye et al., 2022); which could rapidly become a problem as accessing a vehicle equipped with driving automation features is becoming increasingly more affordable. It is therefore essential for any driver to be able to grasp the function of a system, how to use it, how not to use it, and whether they have activated it or not, in an instant. All of this, almost regardless of whether they hold prior experience with the systems available in their vehicle or not. Designing human-machine interfaces (HMI) that can fill this role is a major ever-evolving challenge for automakers, as drivers' responsibilities mutate as their cars' functions increase in numbers and capabilities.

The pictograms (or symbols) used to inform drivers of which driving automation systems are available in their vehicle and whether these systems are currently active, can take different forms for a same system

* Then called "auto-pilot" in the 1958 Chrysler Imperial.

depending on the manufacturer and vehicle model—despite the fact that several symbols were already standardised and advocated by the international organisation for standardization (ISO). This situation could potentially cause confusion among drivers and lead them to not using a system because they do not understand how it would support their driving based on the symbol, to disusing a system that could make their driving safer because the system is acting in a way that was unexpected, or to misusing a system they were yet familiar with because they misunderstood its purpose or confused its symbol for another system. Moreover, inconsistencies reside in the way vehicles will visually present information to drivers about their driving automation systems via the instrument panel, such as the speed targeted by ACC or whether other road users are detected by the vehicle's sensors. These different designs could confuse drivers and impact differently the ease of use, or usability, of these vehicles. To my knowledge, only little research has been conducted to show whether such chaotic state of vehicles' interfaces has real consequences on drivers' safety (e.g., Alarcón et al., 2022; Kim et al., 2022; Li et al., 2017). In addition, how one could address this potential issue, had yet to be determined. Indeed, while the ISO recommends the use of a user-centred design (UCD) approach when designing for safety (ISO 9241-210:2010), examples of research can be found that promote the use of participatory design (Duque et al., 2019), while attempts at designing usable truck HMIs failed to show an advantage of participatory design over UCD because of the lack of expertise of the drivers (François, 2017).

The aim of the present PhD thesis was therefore twofold: ① to show whether symbol confusion was an actual risk and whether the different symbol and HMI designs could have measurable consequences on the vehicles' usability; then, ② to determine which methodological approach could be taken to design symbols and HMIs that would prevent or mitigate said consequences.

Throughout the current chapter, I will more thoroughly introduce the reader to the current state of driving automation and how human factors, that is understanding how humans function, could influence the direction of interface design. More generally, I wish to bring the reader to a certain level of comprehension of humans as perceptive and mobile beings that could add to the reading of the subsequent chapters. Subsequently, I will present my research approach and introduce the chapters in which I report my research.

II. Driving Automation, Drivers, & Interfaces

1. What does automation bring to drivers?

Automation refers to several processes, including the sensing of environmental variables, the treatment of resulting data, decisions, mechanical actions, and or the communication of information via an interface (Sheridan & Parasuraman, 2005). These processes are combined and integrated into common functions to replace human work. Automated functions in motorized vehicles were primarily introduced for the sake of comfort, to relieve drivers of certain routine tasks. Indeed, a meta-analysis shows reductions in drivers' mental workload the higher the level of automation when compared to manual driving (de Winter et al., 2014). Later, as new technologies developed, safety became an important argument for selling vehicles equipped with driving automation systems. A report indicates crash risk reductions ranging from 3% to 81% depending on the system evaluated (Leslie et al., 2019). However, presently, these benefits also come with a cost for drivers, as vehicles capable of handling the entire dynamic driving task from *any* point A to *any* point B are still as much a fantasy as are flying cars.

Table 1.1 Simplified classification and specificities of the driving automation levels (SAE International, 2021).

Automation Level		Accelerating Decelerating	Steering	Detecting & Reacting to Objects	Driving Task Fallback
Level 0	Manual	Driver	Driver	Driver	Driver
Level 1	Assistance	Vehicle	Driver	Driver	Driver
Level 2	Partial	Vehicle	Vehicle	Driver	Driver
Level 3	Conditional	Vehicle	Vehicle	Vehicle	Driver
Level 4	High	Vehicle	Vehicle	Vehicle	Vehicle
Level 5	Full	Vehicle	Vehicle	Vehicle	Vehicle

By 2018, when this project started, partial driving automation, or level 2 (L2), was the highest level of driving automation available. Under the right conditions, the automation controls most of the longitudinal and lateral movements of the vehicle, that is, the acceleration, deceleration, and steering of the vehicle (**Table 1.1**). Yet, it rests in the hands of the driver to monitor both the external and internal environments of the vehicle in case any expected or unexpected technical limitation occurs. Indeed, the vehicle's sensors or computer may fail to detect other road users or objects and crash, sometimes resulting in fatalities as has happened many times already (e.g., Tesla Deaths, 2022). To date, in 2022, conditional driving automation, or level 3 (L3), is the highest level of driving automation available to consumers. The difference with L2 is that the driver's obligation to monitor the environment is removed, and drivers now only have to remain physically available to take over the driving task whenever the system reaches the boundaries of its operational design domain (ODD). This latter details the conditions under which the system was designed to function safely, such as use on motorways, in fluid traffic, and in good weather conditions, for example. The aforementioned automation levels only help define driver roles in a general sense. The ODD, on the other hand, will be specific to each implementation of each driving automation system in a specific vehicle. The said implementation will therefore be the one to define the capabilities and boundaries of the system, and therefore, the exact roles that drivers will have to endorse while using the system.

Terminologies around driving automation have continuously evolved over the years, with the use of certain terms like *autonomous* or *self-driving* becoming prohibited because of their ambiguity or misleading meanings (SAE International, 2021). The correct terminology remains a complex maze, and it is essential to clarify some of these terms used throughout this document before proceeding. Henceforth, an *advanced driver automation system (ADAS)* shall refer to any vehicle system that provides warnings or control over some aspect of the driving task. Therefore, this term should be strictly limited to L0 and L1 systems. Examples of L0 and L1 ADAS are the lane departure warning (LDW) and lane departure prevention (LDP) systems. Then, a *driving automation system* will refer to any vehicle system whose function is to provide control over some or all aspects of the driving task. This term concerns systems from L1 up to L5. For instance, LCC falls under the L2 classification. Finally, an *automated driving system (ADS)*, refers to any L3, L4, or L5 driving automation system that is capable of performing the entire driving task within its ODD—ALKS being the highest level available to date, L3, as previously mentioned.

2. How do drivers need to adapt their driving?

Transitioning from being the sole controller of a vehicle to sharing controls with a driving automation system and, furthermore, being responsible for its good operation, entails a radical shift of paradigm for drivers. Up to L2, the driver holds a supervisory role to fulfil, which requires them to understand how the systems function and what their limitations are to be able to prevent unwanted behaviours from happening, if, and once a system reaches its limits. Equally, the driver needs to understand how to operate each system, and which behaviour is to be expected after interacting with a system's interface: this latter can be composed of buttons, levers, screens, speakers, microphones, and more, to give commands or receive information. In other words, the driver needs to be able to correctly plan the use and commands of the driving automation systems, the first two stages of what Sheridan and Parasuraman (2005) refer to as the *supervisory control paradigm*.

Additionally, the driver should know when, where, and what to look for in the environment and on the interface while using a driving automation system, corresponding to the monitoring stage of the paradigm. For instance, if a driver encounters a traffic jam on the motorway while using ACC, an L1 system, they might want to check their instrument panel to make sure that the system is still active, that it detects preceding vehicles, and that it adapts the vehicle's speed in response to the slowing traffic. But they might also want to look out for other road users who could merge into their lane in such a scenario as ACC usually fails to detect other vehicles cutting in (e.g., Milanés & Shladover, 2016). Intervention would then be the necessary fourth stage of the supervisory control paradigm. Finally, as the fifth stage, drivers may learn from their experiences to better adapt their future expectations and behaviours to each system.

In other terms, drivers need to develop accurate *mental models* of the systems, that is, integrate how to operate the systems and how these systems work or do not work (Jones et al., 2011). Having these models deeply crystallised in mind allows drivers to manage their *attention* more optimally while supervising an automation system (Forster et al., 2019) and potentially avoid situations of mental *overload* (Mehler et al., 2012; Stapel et al., 2019). The latter point holding to the fact that the more drivers know, the lesser the chance of getting surprised by one of the system's behaviours, and the lesser the burden of having to understand what happened and then potentially have to update their mental model (Fukui et al., 2013). Additionally, other factors may come into play when driving automated, such as the trust one puts in a system, secondary task demands, or stress, on which I will not expand in this document (cf. Stanton & Young, 2000).

By seeing how drivers need to adapt to their vehicles, one may start to glimpse at how vehicles should be adapted to reduce the friction that drivers may experience when using driving automation systems, whether it is for the first time or the hundredth time.

3. How do automakers need to adapt their vehicles?

Ergonomics can be defined as ① the scientific study of how human factors interplay in interactions with other humans, systems, or any other element present within the environment, or, as ② the application of our knowledge about human factors to the better design of human interactions (Dempsey et al., 2006). Ergonomics can help design more *usable* HMIs, that is, HMIs that are easy to use, to remember, that help achieve one's goals accurately, with few resources, and that are pleasing to use (Nielsen, 1994). Applied to vehicles equipped with driving automation systems, this translates into HMIs that support the driver in their roles as controller, up to L1, as supervisor, up to L2, and as a passenger from L3 and beyond. For instance, and more concretely, this could involve having an interface that makes it easy to understand the function of a button, how to activate a specific function one would have used before, not activating the wrong function by mistake, being able to see rapidly whether the right function has been activated or not, and not being dissatisfied with any of these steps along the way. This example purposefully illustrates cases where symbols could play a major part in the interaction, while also showing that ergonomics matter both for the sensorial and physical aspects of an interface.

In terms of sensorial aspects, for instance, research has shown that take-over requests were more efficient at capturing drivers' attention via multimodal signals rather than visual signals only (Naujoks et al., 2014; Petermeijer et al., 2017). On the other hand, regarding the physical aspects, attention-guiding seats that would slightly rotate the driver towards other passengers during L3 automated driving and rotate them back in a neutral position when taking over is necessary (Jochum et al., 2022) were designed on the basis of the multiple resources theory of attention (Wickens, 2002). This theory postulates that each sensorial channel would run in parallel to other channels and have dedicated resources, implying for example that auditory signals would not interfere with visual signals. Therefore, the authors argued that at the time the seat would rotate the driver back into a driving position to signal a take-over request, the kinesthetics and vestibular sensory channels would not compete with the visual and auditory channels of the driver, who could be engaged in non-driving related activities such as conversing with other passengers. However, other interpretations not based on the multiple resources theory can be made.

Summary

To summarise this first section, I explained how driving automation imposed new roles on drivers, notably as supervisors, for which they need to develop appropriate mental models of the driving automation systems. Drivers need to be aware of what each system's function is, what their limits are, and whether the systems are operating safely while they are using them. Some of the roles of the HMI are to allow drivers to activate these systems easily and support drivers in their supervisory tasks, including helping drivers attend the information they need and alleviate the charge on drivers' mental workload. Developing and activating the right mental models during automated driving is therefore essential for drivers, and HMIs need to facilitate this process. To understand how graphical symbols and visual aids on the HMI could help achieve this, one needs to explore how visual perception is intimately tied to motricity and how our visual system is wired to perceive interaction opportunities.

III. Understanding Humans & Perception

1. Why do we perceive?

Neurobiologist Pr. Daniel Wolpert, in a presentation at the Society for Neuroscience meeting of 2009, suggested that our human brains evolved to be so complex not so that we could think but rather so that we could be mobile (The Kavli Foundation, 2010; Wolpert, 2009). Sensation and perception would have emerged so as to direct our motricity, starting from being rather simple organisms merely directed towards the light (Wolken & Shin, 1958) to complex living beings using photons to build and maintain internal representations of their (visual) environment.

2. How do we perceive?

According to the *proactive brain* framework (Bar, 2009a), sensorial information would be analysed in light of what the brain has already learned. As such, those established internal representations mentioned previously serve to interpret our environment rapidly and with less effort but they can also serve to discriminate novel information from information seen previously (Barbeau et al., 2017). In fact, our whole sensorial system may be seen as a change detector as, down to the cellular level, our sensorial receptors adapt their responses to prolonged exposures to a signal until this latter changes (e.g., Clark et al., 2013)—which explains why we sometimes forget that we are wearing our glasses. Any piece of information that contrasts with its surroundings or with prior information will be perceptively emphasised and guide our attention towards it in a *bottom-up* automatic fashion (Evans et al., 2011). For example, a red blinking symbol on an instrument panel will easily attract our visual attention on the condition that not everything around it is also red and blinking. Nonetheless, our attention can also be directed by our goals, such as looking for a specific symbol on the instrument panel in order to check whether an ADAS is currently active. This *top-down* mechanism facilitates the perception of stimuli that match specific representations held in our working memory (e.g., the symbol) and helps guide our attention towards these stimuli automatically (Evans et al., 2011). Finally, according to the *grounded cognition* theory, the perceptual representations held in memory by the circuitry of our brain are multi-componential (Barsalou, 2008). In other terms, this means that the representation of a steering wheel not only includes how it looks, but also how it feels to the touch, the sounds it makes when being grasped and steered, the position of our body when we use it, the emotions we may be feeling, and importantly, the actions and outcomes that are possible to produce with it.

3. What do we perceive?

A. Affordances

Those actions associated with an object, like holding and steering a wheel, are referred to as *affordances*: they are the actions made possible to an individual by the environment given their physical attributes (Gibson, 2014). Furthermore, one's perception of space and objects changes to adapt to the tools and objects they may be using. Studies have shown that using objects can extend the space that we humans perceive is interactable and can facilitate the recognition of contextually-related objects (Brockmole et al., 2013; Holmes, 2012). Driving a vehicle can affect our perception as it has been reported that drivers underestimate distances after driving compared to pedestrians because the speed of locomotion is different (Moeller et al., 2016). Before even formulating his theory on affordances, Gibson co-theorised the *field of safe travel* that drivers would perceive, whose repelling boundaries would be defined by road markings, road users, and animate or inanimate obstacles such as humans, other animals, or rocks (Gibson & Crooks, 1938)—interestingly, children, for instance, might usually be perceived as very approachable and *positively valenced* when on foot, whereas while driving it might be preferable to avoid them, and therefore they will be perceived as *negatively valenced*. Nonetheless, a study suggests that space perception is not affected when one sees an action being automated by a machine (Tenhundfeld & Witt, 2020). Hypothetically, the effect observed by Moeller et al. (2016) should thus differ between drivers and passengers or between drivers driving manually and drivers using driving automation systems since their affordances would not be the same. Indeed, the intent of using a tool is essential for observing the effect of tool use (Witt et al., 2005) since the effort necessary for carrying an action is accounted for and influences our perception (Proffitt, 2006, 2009), even when observing someone do the action (Witt et al., 2014).

This field of research remains much in line with how affordances were framed by Gibson (1979; see also Osiurak et al., 2017). The concept has much evolved since then, most notably thanks to Donald Norman (2013) in the design field, but also later to not only consider the purely physical aspects of affordances but also their effects, short or long term. Indeed, Pucillo and Cascini (2014) developed a framework taking into account the importance of users' goals and conceptualised *manipulation affordances*, *use affordances*, *effect affordances*, and *experience affordances*. To illustrate, pressing a button on the steering wheel will correspond to a manipulation affordance, similar to how Gibson (1979) first defined affordances. Then, correlating that pressing this particular button will activate ACC because the symbol is printed on it would be an effect affordance. These two steps would consequently lead to the possibility of driving while removing one's feet from the pedals, which would be the use affordance of ACC. Finally, cars today can offer different experiences, such as driving manually or automated, driving with an L2 or an L3 system, etc. Via these modes of driving, one may look for a more relaxed type of drive or for the satisfaction of driving a sensational car: these would correspond to experience affordances.

One may now wonder whether drivers can perceive these use and experience affordances similarly to how they perceive manipulation affordances. That is, knowing whether looking at a button or the ACC symbol on a button will activate our mental model of how ACC works and how it feels to be using it. Unfortunately, no technology is yet capable of showing us how such high-level mental models activate in the brain as these involve very dynamic processes, both spatially and temporally (see Thagard, 2010). Gibson himself would not have had supported this idea as his ecological approach on affordances rested on the postulate of 'direct perception', which denies any need for mental representations or inferential processes to occur between perception and action (Chong & Proctor, 2020). This view, however, is challenged by more modern accounts of neurosciences (de Wit et al., 2017) and grounded cognition (Barsalou, 2010): indeed, research has shown that the mere perception of actionable objects potentiated the activation of the cortical regions involved in their perception/manipulation and could influence the execution of subsequent unrelated motor actions (Ellis & Tucker, 2000). These cortical regions are arguably the basis for mental representations, and mental models merely the arrangement of perceptual-motor representations to allow for predictions in a spatially and timely manner, and to guide the execution of goal-directed actions (Khemlani et al., 2014).

Theoretically, nonetheless, research showed that affordances are represented in our brain and all one needs are the right cues to fire the right neural pathways and associate the right concepts (Bar, 2009b). For instance, reducing the visual cues that indicate affordances on a website increases the time spent on the webpage and increases the dispersion of the users' eye gazes because their attention is not oriented effectively (Moran, 2017). Additionally, it is known that attention is directed towards stimuli that are emotionally charged (Schupp et al., 2007) and that emotions are thought to be the perceptions of our bodily states in response to (or simply during) an event, and that these tint our experiences, retrospect, present, or prospect (Withagen, 2018). Using the

Thai road sign for refreshment shops as an example, the modified sign shown in **Figure 1.1** should in theory orient drivers' attention towards pleasant feelings of warmth and coffee smell via the added vapour, the beans, and the brown colour (which in reality could not be used for this purpose). The bottom of the mug was also made more incurved to recall the mugs usually used in coffee shops. Although these two versions of the same road sign actually afford the same experience, drivers should perceive different affordances because different signifiers were used, that is, the signs in the environment that make affordances perceivable (Norman, 1999, 2013).

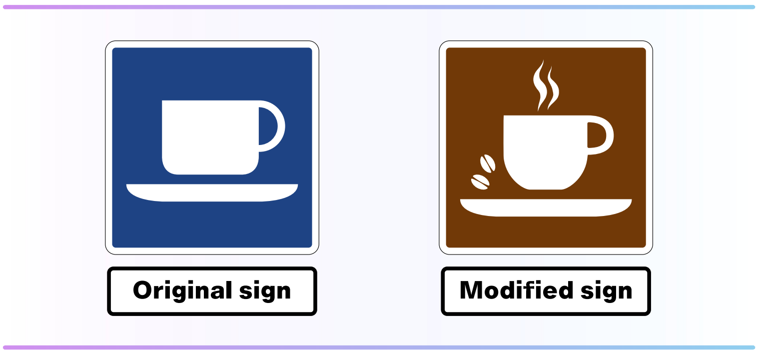

Figure 1.1 Thailand's road sign for refreshment shops (left) and a redesign to attract the viewer's attention to the emotional values associated with the experience of enjoying a coffee (right).

Therefore, recalling a whole mental model or experience affordance may not be achieved by the simple view of a plain physical button, but by using the right signs to build up enough evidence to match and reactivate a specific mental model. As we approach the end of this literature review, one may wonder then: what makes a sign 'good'?

B. Signs

In semiotics, "the science of signs" (Marcus, 2003, p. 38), signs are any "perceivable (or conceptual) objects that convey meaning". A good sign, therefore, will simply be a sign that conveys its meaning accurately to its target audience. But there are different media for conveying meaning: icons, symbols, pictograms, ideograms, and signals, are some of the different types of signs that exist.

- *Icons* are signs that are self-evident, natural, or realistic—e.g., ⬅ an arrow showing left, or, a photograph.
- *Symbols* are signs that are conventional and often abstract—e.g., ⛔ the 'No entry' sign or the United Kingdom flag.
- *Pictograms* are icons or symbols that have clear pictorial similarities with their signified—e.g., ♿ the international symbol of access.
- *Ideograms* are symbols that stand for ideas or concepts—e.g., 車 stands for 'vehicle' or 'car' in Japanese/Traditional Chinese.
- *Phonograms* are symbols that stand for sounds—e.g., し and シ in Japanese sound similar to the English word "she".
- *Signals* are signs whose purposes are generally to incite behaviours (Frutiger, 2004)—e.g., ⚠ a 'Warning' sign.
- *Indexes* are signs that show relations of cause and effect in space and time—e.g., 👣 footprints, or, smoke to indicate a fire.

As suggested by the different types of signs listed, designing visual signs can be based off of different types of graphical representations (e.g., abstract or concrete), and different types of elements can be combined to form a single metaphor or analogy. The term 'icon' has been predominating in the context of personal computers and user interfaces (UI), defined simply as a "graphical symbol", regardless of the composition of the sign (Blankenberger & Hahn, 1991; Gittins, 1986). The ISO uses the term 'symbol' for use on vehicles (e.g., ISO, 2010a), however; also, I will use this denomination for the rest of the document.

McDougall et al. (1999) proposed five characteristics to take into account when designing symbols: *concreteness*, *complexity*, *meaningfulness*, *familiarity*, and *semantic distance*. Research showed that road signs designed by following such ergonomic principles were more easily understood and remembered than other symbols (Ben-Bassat, 2019). In terms of concreteness, Alla Kholmatova (2013), designer, observed that people tended to try and interpret signs as icons when they were not familiar with them, making abstract signs more likely to be misinterpreted or simply impossible to interpret. Congruently, road signs that resembled their signified were more easily matched to their description by students who did not have any driving experience compared to abstract symbols (Chi & Dewi, 2014). Nonetheless, one may depict concrete objects and still have meaningless symbols if the semantic distance between the sign and its significant is too large. For instance, on a smartphone, one may want to represent a photograph as an index type of sign for the camera function. However, this sign could also be an icon for the photo gallery, which is closer semantically to this function than a photograph is to the camera function (e.g., Gatsou et al., 2012). As such, symbols in a set need to be as close to their concept as possible but as far as possible from other symbols and their concepts to avoid confusing them (Silvennoinen et al., 2017).

Ultimately, concreteness does not necessarily correlate with meaningfulness and abstract symbols may be used on the condition that the target population is familiarised with them before they have to use them in context (Gatsou et al., 2012), especially if safety is a concern. Arrow signs (e.g., ➡) for instance, which are abstract in nature, have become so universal that they can direct our spatial attention and prime motor intention areas of our brain in a matter of centiseconds (Praamstra & Kourtis, 2010). Familiarity, therefore, may matter as much as concreteness. In the case of driving automation system symbols, more and more drivers should progressively get familiarised with them as of recently, the French driving theory test includes questions about CC and ACC; but not about LCC or ALKS, albeit this latter system has been approved for use in the country (see Auto-IES, 2021; Canopée SAS, 2022). More drivers should therefore get acquainted with the ISO symbols in the future. Still, in a study, 6 out of 13 ISO safety symbols were still poorly understood (< 50% comprehensibility), of which many had not been tested for comprehension according to the authors (Davies et al., 1998). Two other studies showed that alternative symbols could be preferred over some ISO symbols used in vehicles or for road signs (Payre & Diels, 2019; Sayer & Green, 1988). Although drivers may get acquainted with driving automation system symbols during their formation, they may not use these symbols for a long time after obtaining their driving license. Thus, these symbols should be rememberable and distinct enough to prevent confusion when drivers get the chance to use them again. Symbols for driving automation systems are safety critical and differ from other car symbols at least in that they are associated with shifts of responsibility between the driver and the system; drivers need to accurately understand their functionality as these systems can be actively involved in the driving task and can be associated with problematic behaviours such as complacency or misuse. Symbols used for the heating system, for instance, are also found in vehicles and could engender driver distraction, but wrongfully activating the heater will not provoke a sudden lane change or deceleration that might surprise other road users or the driver.

C. *Summary & research gap*

In this section, we have seen how our perception was intimately tied to our motricity and programmed to analyse our environment in terms of interactions or affordances. Our small-scale internal representations of the world and how this latter operates—our mental models—are multi-componential and integrate as much our affordances as our sensorial percepts. These affordances can either be direct manipulation of objects, like pressing a button, or more complex abstract concepts such as the exciting experience of driving a handless L3 system. We also saw that to perceive affordances we needed visual cues, or signifiers, to attract our attention and activate the appropriate chain of concepts, and eventually, our mental models. These signifiers can be concrete and naturalistic, like the shape of a steering wheel, or can be more abstract, like an arrow indicating a direction or road markings that indicate a safe field of travel for the driver. In the case of abstract signs, however, it is important that the subject be familiarised with them to interpret them correctly and to be able to remember them later on. Driving automation systems are more and more specific and still insufficiently taught to drivers. Therefore, familiarity with these systems is rather unlikely and needs to be bypassed, somehow, when designing symbols and HMIs.

Driving automation will impose a supervisory role on drivers for as long as human intervention will be necessary at some point during the drive, be it only for activating an L3 or L4 system and making sure it is operating. Drivers, therefore, need to develop appropriate mental models of the driving automation systems and, up to L2, to satisfactorily distribute their attention between the different tasks involved in driving. One role of the HMI is to facilitate the activation of appropriate mental models via well-designed graphical symbols and visual aids presented on the instrument panel or head-up display. Currently, many designs exist for a same system, each making use of different visual signifiers that may inconsistently affect usability and cause confusion. In addition, some systems are very similar to one another, making semantic distance an important issue for symbol design that could also cause confusion among drivers. The two latter points constitute the first problem that I will try and address throughout this thesis, as little research has been conducted that showed that the different HMI designs on the market could cause confusion and harm usability, similarly to how ADAS differences between vehicles can confuse drivers (Oviedo-Trespalacios, 2022). The second problem was to explore a methodological approach that could allow researchers and designers to address similar problems in the future, and whose foundations will be exposed in the next section.

Therefore, again, the scope of the present PhD project was twofold: ① to show that symbol confusion was an actual risk and that the different symbol and HMI designs could have measurable consequences on a vehicle's usability, but also ② to determine which methodological approach could be taken to design symbols and HMIs that would prevent or mitigate these consequences.

IV. Research Approach

1. Usability: definition and relevance for safety

Although the term can be defined as simply as the 'ease of use' of a product (e.g., Shackel, 2009, p. 362), usability is more commonly defined by the qualities that a product should have according to the standard definition of usability given by the ISO as being 'the extent to which a product can be used by specified users to achieve specified goals, with effectiveness, efficiency and satisfaction in a specified context of use' (ISO 9241-11:1998). Nonetheless, various authors have proposed their own variation of the concept. For instance, I have previously cited Jakob Nielsen (1994), but one can also find the definitions given by Brian Shackel (1990), Patrick Jordan (1998), or Whitney Quesenbery (2003), non-exhaustively; their differences residing mainly in the qualities that a usable product should have (**Table 1.2**). While some of these qualities may be common across definitions their definition can still differ between authors. For instance, Nielsen (1994) defines efficiency as the level of productivity one can achieve with a product, whereas this definition would correspond to effectiveness as it is defined by the other authors, who would define efficiency as the resources spent to reach a satisfying level of performance. Jordan's (1998) definition will not be detailed here as it deviates too greatly from the other definitions to be concisely introduced.

Table 1.2. Highlight of the usability components that are similar between four definitions. Italic: components that do not have equivalents in other definitions.

Shackel (1990)	Nielsen (1994)	ISO (1998)	Quesenbery (2003)
Effectiveness		Effectiveness	Effectiveness
	Efficiency	Efficiency	Efficiency
Attitude	Satisfaction	Satisfaction	Engaging
Learnability	Learnability		Ease to learn
	Errors		Error tolerance
Flexibility	*Memorability*		

Evaluating the usability of a product, consequently, involves measuring several of its aspects. According to the ISO (ISO 9241-11:1998), the effectiveness of a product refers to the extent to which a task can be achieved by a user and can be measured by the number of tasks completed, number of errors, and the quality of the output (see also Bevan et al., 2016). The efficiency, defined as the amount of effort required to use a product, can be measured by the task completion time and user's mental workload. Finally, satisfaction is simply the level of comfort felt when using a product and how acceptable it is to use, and can be measured via quantitative or qualitative attitudinal metrics. These measures may be collected via empirical methods, such as focus groups, user workshops, think aloud protocols, field observation, questionnaires, interviews, controlled experiments, et caetera; but they can also be collected via non-empirical methods, like for instance, during task analyses, expert appraisals, cognitive walkthroughs, or more (see Jordan, 1998).

Usability has, therefore, an important link to safety and is an important quality to consider when designing driving automation systems and their associated HMIs. Notably, improving the effectiveness of a driving automation system reduces the risks of a driver making use errors and makes sure the system behaves as expected. Efficiency ensures a product or system can be used with only little attentional or mental demand from the user, who can therefore keep using the product or system appropriately for longer periods. Finally, improving the satisfaction of using a system increases the chances of drivers using a driving automation feature that can increase their safety. Usability was therefore a key concept of this thesis due to its relation to safety.

2. Why use a mixed-method approach?

In my approach to this research, I have adopted a *pragmatic* worldview while still adhering to a *postpositivist* worldview (see Creswell & Creswell, 2018). Postpositivism follows the conventional deterministic and reductionist philosophy governing the scientific method. Pragmatism, on the other hand, puts an emphasis on the research problem rather than the methods per se, and leads the researcher to take a pluralistic approach in order to take advantage of the methods and data analyses that would work best at a given time for the problem at hand. This may lead a researcher to use both *quantitative* and *qualitative* methods of research. In the present case, usability is a multicomponential concept as well as a part of a subjective user experience for each driver (Sauer et al., 2020). This subjectivity aggregated to the necessity of understanding how drivers mentally and visually represent driving automation features are arguments in favour of using qualitative methods. Nonetheless, usability and improvements on safety are also measured by means of quantitative metrics. Consequently, a *mixed-method* approach was used throughout this research.

3. Which design approach(es) to use?

Design approaches are plural, but the ISO recommends in particular the user-centred design (UCD) approach, sometimes also referred to as human-centred design (ISO, 2010b). In this approach, the user is involved in the design process as a test subject in order to identify their needs and observe their behaviours while they use prototypes or finished products (Dell'Era & Landoni, 2014). Non-exhaustively, this approach may include the use of questionnaires, interviews, focus groups, ergonomics, or usability testing. A second design approach, however, was also considered and combined for this project: participatory design. The difference between participatory design and UCD being that users are considered as "active co-creators" rather than simple "reactive informers" (Sanders, 2006). In other words, potential or current users can potentially be involved throughout the design process to help define problems, find solutions to these problems, and evaluate the designs. The advantage of participatory design over UCD would therefore be a deeper understanding of users' needs. However, one needs to account that users are not experts and that their involvement in decision-making has not necessarily been associated with benefits for usability (Bailey, 2005; Marti & Bannon, 2009). Mathilde François (2017), who systematically compared the two methods in several studies of her doctoral thesis, found that truck HMIs designed using the UCD approach were more or as usable as the HMIs developed using a participatory design approach. She concluded that drivers were indeed poorly habilitated to make good design decisions but that allowing them to choose between several expertly-crafted designs could benefit the subjective and objective qualities of HMIs. Therefore, participatory design was mainly used as a way to assess drivers' mental models during the early stages of the present project, but not onward, where UCD will be preferred.

4. Thesis outline

Consequently, I conducted market research using car manuals, manufacturers' websites, and demonstration videos, as well as review videos, to identify and index the symbols used for the different systems available at the time, as well as the different designs available for displaying information about the ACC and LCC systems particularly, as these systems were the ones with the most visual design inconsistencies and are both automating a major aspect of the driving task; namely, the longitudinal and lateral controls, respectively.

To investigate whether symbol confusion was a risk for drivers and whether the different symbols and HMI designs could have measurable consequences on a vehicle's usability I firstly planned (Research Question 1) to investigate how the ACC and LCC systems were visually represented in drivers' mental representations using a participatory design approach, then (RQ2.1) to assess which ACC and LCC symbols would be best understood by drivers and (RQ 2.2) which symbols would be less confused with other ADAS symbols using an UCD approach. Thirdly, using only an UCD approach and based on the results obtained at this point, I wished (RQ3) to investigate whether a suite of symbols designed around the concept of affordances would be more usable than the recommended symbols. Finally, one study was dedicated to (RQ4) comparing the usability of different HMI designs for the ACC system using an UCD approach. The chapters, however, will present the studies in chronological order, each referring back to the previous research to explain the links between them. Hence, RQ4 is explored in Chapter 4 whereas RQ3 is explored in Chapter 5. The outline of this thesis is graphically summarised in the **Figure 1.2** following this section.

Chapter 2 answers RQ1 and reports the results I obtained after conducting a participatory design workshop during which I asked drivers to produce their own symbols for the ACC and LCC systems, as they were the ones with the most use inconsistencies on the market. I also asked drivers to review the different symbol designs that could be encountered in the automotive market. These results helped me first envision how the concepts of interactions and affordances could be important for drivers and helped me select which symbols should be further tested.

Chapter 3 answers RQ2.1–RQ2.2 and reports the results from an online survey that was conducted to evaluate the recognisability of several symbol designs for the ACC and LCC systems. The method approach was adapted from the Federal Highway Administration, or FHWA (Campbell et al., 2004), somewhat similar to the approach predicated by the ISO

(International Organization for Standardization, 2014), but that also includes a matching test in addition to the comprehensibility test. This matching test is important as it accounts for the symbols that would be used alongside the symbols tested. In our context, this was an important thing to consider as it could allow to detect the problems that could arise when using certain symbols together. Consequently, the results from this study informed separately the studies presented in **Chapters 4** and **5**.

Chapter 4 answers RQ4 and reports results from a simulator study in which three HMIs designed for the ACC system were compared on their usability aspects. More specifically, different ACC symbol designs were tested and a speedometer was designed to help drivers better understand their ACC system. An eye-tracking device was used to measure drivers' visual attention, and drivers' completion times were also measured during several use cases. Additionally, questionnaires and semi-directed interviews were used to evaluate drivers' workload and the usability qualities of the HMIs.

Chapter 5 answers RQ3 and reports the result of a second simulator study in which two sets of symbols for the CC, ACC, LDP, LCC, and ALKS systems were tested and compared: one consisting of standard and recommended symbol designs and one that was mostly consisting of symbols validated during this PhD project. Drivers were video recorded while they were driving and thinking aloud. Concurrent probing (i.e., prompting drivers to answer questions) was also used to complement the thinking-aloud technique. These recordings were then analysed and coded to extract measures of mental model errors and mode confusions. Additionally, questionnaires and semi-directed interviews were again used to measure workload, usability, but also drivers' preferences.

To conclude, **Chapter 6** closes this thesis by summarising and discussing the original results hereby presented, their implications, and to suggest directions for future research.

All studies have been approved by the Social Sciences, Environment and LUBS (AREA) Faculty Research Ethics Committee of the University of Leeds under the references LTTRAN-103 [Chapters 2–3], LTTRAN-122 [Chapter 4], and LTTRAN-133 [Chapter 5].

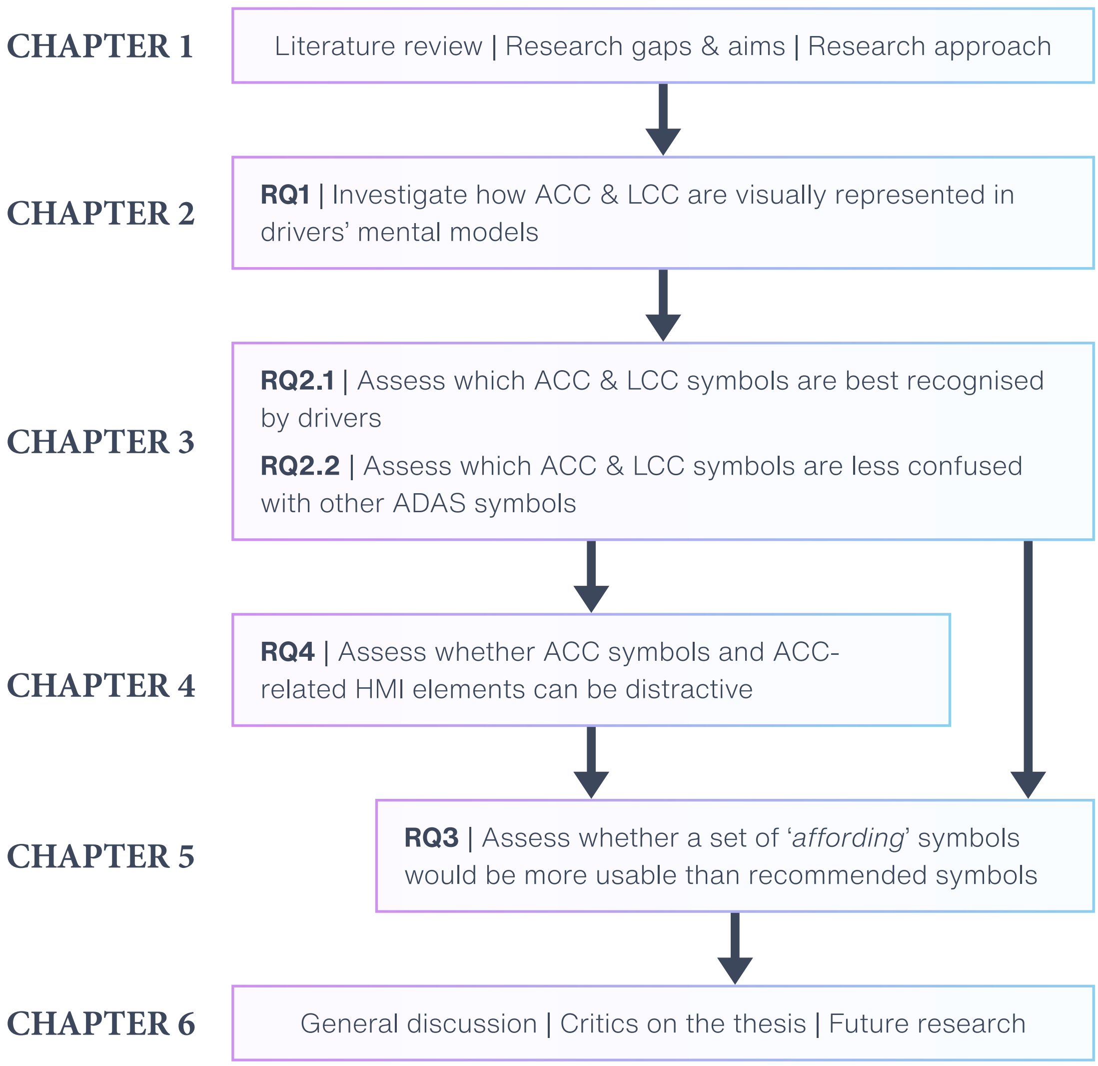

Figure 1.2 Hierarchy of the thesis' chapters and respective themes treated.

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Chapter II

Applying Participatory Design to Symbols for SAE Level 2 Automated Driving Systems

ABSTRACT

Automakers take the risk of designing their own symbols for adaptive cruise control (ACC) and lane centring assist (LCA), some of them even using symbols from other driving assistance systems. Doing so exposes drivers to potential confusion and poses a threat to safety. A user-centred approach allowed us to gather information on ways to design intuitive symbols for users of automated vehicles. We invited drivers to a participatory design workshop to ideate and review existing symbols used for ACC and LCA. Here, we report our first step towards the development of recommendations for the design of driver-vehicle interfaces (DVI) of SAE level 2 and 3 systems.

I. Introduction

SAE level 2 automated systems (SAE International, 2018) combine adaptive cruise control (ACC) and lane centring assist (LCA) to relieve drivers from longitudinal and lateral control, respectively. To indicate the status of a driving assistance system, automakers sometimes diverge from ACC's standard symbol (**Figure 2.1**), while no standard exists for LCA. Consequently, symbols for different driving assistance systems are exchanged: Nissan (2018) uses the lane keeping assist (LKA) symbol for lane departure warning (LDW), and Toyota (2019) uses the LDW symbol for LCA, for instance.

Symbols for driving automation systems should be intuitive to prevent confusion and misuse (Parasuraman & Riley, 1997). Intuitiveness implies fast and effortless processes, as it does not involve conscious reasoning or analysis (Hurtienne & Blessing, 2007; Reddy et al., 2009). Symbols are not considered in current guidelines on HMI (Campbell et al., 2004; Naujoks et al., 2019) for automated vehicles. In a step toward proposing symbols that drivers could easily recognise and differentiate, we conducted a participatory design (Sanders, 2002) workshop, involving drivers in the design process. To provide the rationale behind symbols design, in this paper we present an analysis of the symbols produced and the comments expressed about existing symbols.

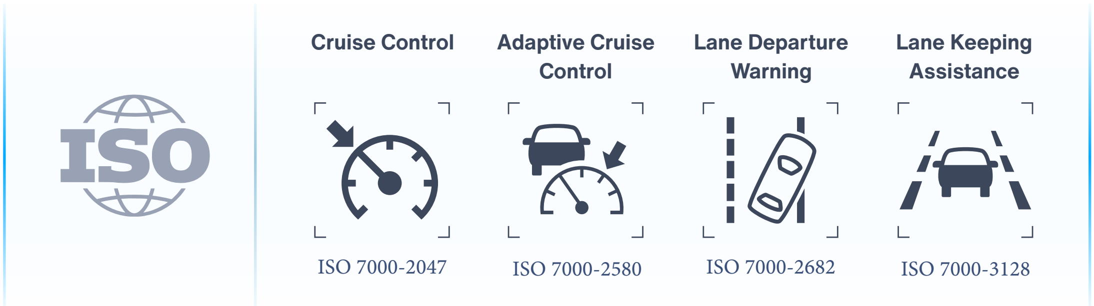

Figure 2.1 From left to right, standard symbols for cruise control (CC), adaptive cruise control (ACC), lane departure warning (LDW), and lane keeping assistance (LKA). ISO 7000:2047, 7000:2580, 7000:2682, and 7000:3128.

II. Methodology & Analysis

1. Participants

Six British drivers (5 males) aged from 26 to 55 years old, and one Australian female driver aged 29, attended our workshop (μ = 38.7). Only the males were familiar with cruise control, one also being familiar with LDW. Except for the Australian driver, all participants drove regularly in the U.K., and none worked in engineering or design.

2. Automakers' symbols & original concepts

The systems studied here were those tested by the Euro NCAP (2018). Symbols were extracted from owner's manuals, or automakers' or users' videos, and redrawn for visual consistency (**Figure 2.2**). Cadillac's Super Cruise was added to the list (General Motors LLC., 2019) along with an ACC symbol previously used by Volkswagen (2013). Additional symbols were designed with an ecological approach to the driving task (Gibson, 1979). **Figure 2.2.h** depicts pedals to represent the interface of the car used by drivers for longitudinal control, rendered redundant by the use of ACC. **Figure 2.2.c** represents the movement of the driver's car moving towards a lead car as the result of using ACC. In **Figure 2.2.k** & **Figure 2.2.m**, grey hands were added to illustrate the demand from drivers to keep their hands on the steering wheel whilst remaining passive. These concepts were not covered by automakers, but it was important to ensure that they would be discussed.

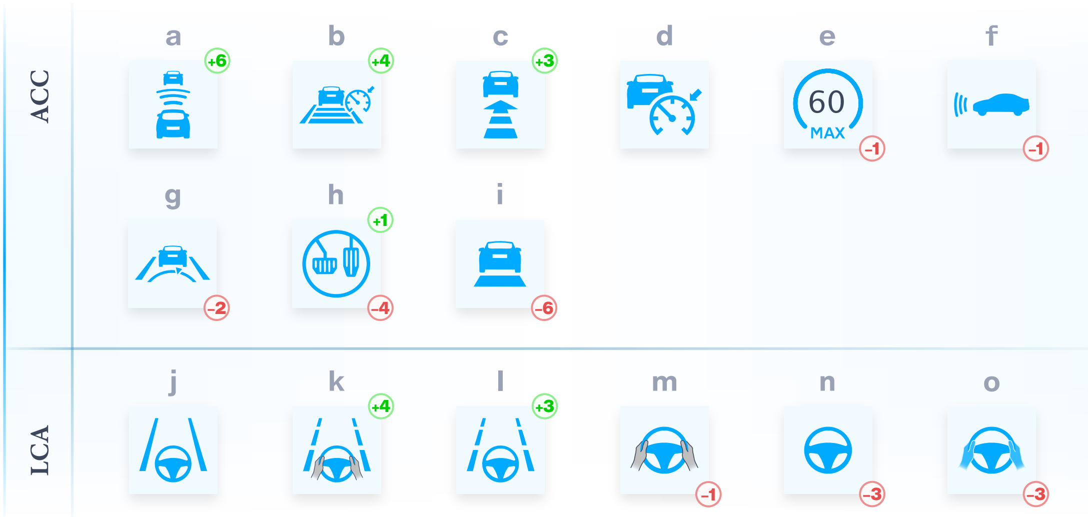

Figure 2.2 The ACC and LCA symbols that were reviewed and scored during the workshop. The positive scores in green indicate the number of times a symbol was chosen as the most or second most understandable ACC symbol, or as the most understandable LCA symbol. The negative scores in red indicate the number of times a symbol was chosen as the least understandable or second least understandable for ACC only.

3. Workshop procedure

The workshop started with a design ideation phase where participants were given written descriptions of four driving assistance systems (CC, ACC, LKA, and LCA) and asked to imagine what symbol should appear to be able to understand that ACC and LCA had been activated. We stressed that participants should only focus on their own opinion and not be concerned with how others would perceive them. A pile of blank A4 pages was provided to sketch their ideas using a pencil. After 20 minutes, they had to choose two of their designs for each system and redraw them properly using a black pen in separate frames (12 × 12 cm). Each presented their designs and explained their process. During a review phase participants commented on existing symbols, all presented on a display (minimum size: ≈40’ arcmin) [see Naujoks et al., 2019]. Supplementary explanations were asked where relevant. During a scoring phase, participants were to choose the two ACC symbols they thought were the most understandable and the two that were the least. For LCA symbols, they only chose one of each as there were few designs to choose from. Finally, given all the designs they had seen so far, they drew one symbol for each function they thought was the most appropriate.

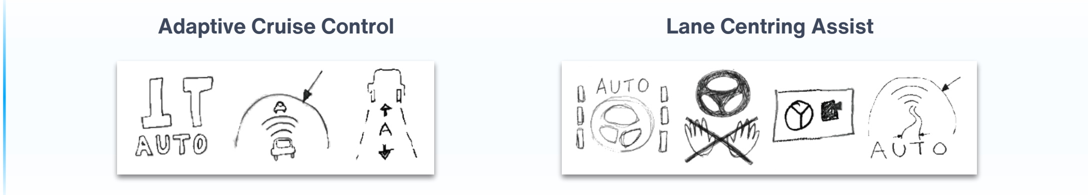

Figure 2.3 Samples of sketches for adaptive cruise control (ACC) and lane centring assist (LCA).

A. *Ideation phase: ACC*

Three main themes emerged from the drafts collected (**Figure 2.3**):

- *Interaction*: the parts of the DVI that drivers use to conduct the driving task are represented to indicate their redundancy when using ACC (i.e., the pedals). This approach only received marginal success.

- *Descriptive*: the way drivers understand the system is represented. Symbols can illustrate the sensors (RADAR and cameras), the set speed (numbers and speedometers), the set distance (bars or arcs), and the word “AUTO” was largely used to easily indicate “automated”. Additionally, one participant used the acronym of the system, and one wrote “A” instead.

- *Representational*: the way the system’s operation translates into a phenomenon observable by drivers. Arrows were used to represent the acceleration and deceleration, or the distance between vehicles. A driver-centric view was largely adopted for symbols’ design. Speedometers are the main means by which drivers monitor their speed while driving, and lead cars were mostly depicted as they are seen from the driver’s seat (i.e., from the rear).

B. *Scoring & review phase: ACC*

From the choices made (**Figure 2.2**), it seemed essential for drivers that the following distance be represented. Showing both the ego and lead cars could better illustrate the concept of headway distance. Secondly, representing the set speed was also important, but on its own, describes only poorly what drivers know of ACC. Note how the ACC standard symbol (**Figure 2.1**) does illustrate speed but lacks a concept of distance. Descriptive symbols require knowledge of the system, and therefore might not necessarily be intuitive for naïve drivers. Finally, participants disfavoured ambiguous symbols: symbol **Figure 2.2.g** depicts a speedometer that was confused for a steering wheel, symbol **Figure 2.2.i** fails to represent the headway distance using a trapezoid, and symbol **Figure 2.2.h** is too vague and seems only to prompt an action whilst also resembling a traffic sign.

C. *Ideation phase: LCA*

The description given for LCA stated that drivers did not need to hold the steering wheel, in the prospect of SAE level 3 systems being allowed on the road. Four themes were extracted from participants' sketches (**Figure 2.3**):

- *Affordances*: the visual cues from the environment used during the driving task, rendered redundant by LCA, are depicted. A steering wheel and lines were widely used to represent the DVI and the elements defining the "field of safe travel" of drivers (i.e., their lane) (Gibson & Crooks, 1938). The lines were designed by some participants to represent the affordances offered in real context: continuous lines are never meant to be crossed whereas dashed lines sometimes authorise crossing. This was projected onto the system where continuous lines would indicate a safer system as compared to dashed lines, implying a system leaving some control and responsibility to drivers.

- *Interaction*: the action usually executed by drivers to conduct is emphasised. Thus, hands are depicted off the wheel and can even be crossed to show their redundancy. Contrasted hands indicate clearly that drivers are left with some responsibility.

- *Sensors*: the sensors used by the system are depicted, that is, a forward-looking camera, demanding a certain knowledge of the system.
- *Combined*: it was important to some participants that both ACC and LCA were combined into one symbol to make them simpler and faster to read.

Acronyms were again used to facilitate readability and interpretation. However, the use of "AUTO" alongside symbols can be risky as this abbreviation could either mean "automated" or "autonomous", the latter being inaccurate considering the actual capabilities and demands of SAE level 2 and 3 systems.

D. Scoring & reviewing phase: LCA

Symbol **Figure 2.2.j** was not included in this part to not disturb participants in their decision-making as it was formerly thought that lines' design was mostly artistic. This did not prevent participants to discuss it spontaneously. The presence of vertical lines seemed crucial for the understandability of symbols as those devoid of them were disfavoured. Grey hands were preferred over no hands or isochromatic hands, the former representing more the action expected from drivers when using the system. Again: drivers disliked ambiguous information.

E. Final designs

Some of the participants took the liberty to enhance their original designs (**Figure 2.4**).

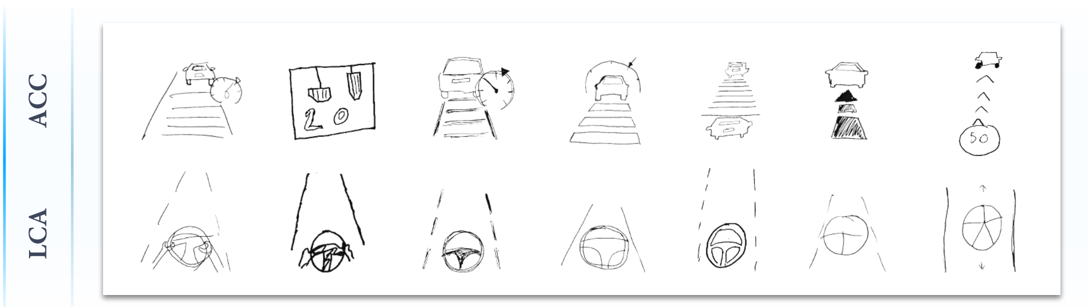

Figure 2.4 Participants' pairs of sketches from the final phase.

III. Discussion

In this preliminary study phase, we gathered valuable information on how drivers understand driving assistance and how they would conceptualise symbols given the information provided by automakers in their owner's manuals. We found that a driver-centric view was largely preferred over a system-centric view. The former approach allows to present information in a way that makes the most sense for drivers: depicting the input of an action (e.g., pedals) or the output of that action (e.g., speedometer), as it is usually observed by drivers, could allow symbols to be easily recognised since the presented information would be very relatable for drivers. Thus, the way the system is built is not as crucial as the context and how the system will assist drivers. The visual cues useful for conducting the driving task were equally essential. The concepts of speed, headway distance, movement, and, to a lesser extent, interface, were critical for ACC symbols. For LCA, continuous lines, the hands, and a steering wheel were all crucial to represent the driving task taken over by the driving assistance system. DS or Ford are examples of LKA and LCA symbols in line with the present findings.

The insight presented may help develop guidelines for the design of DVIs for SAE level 2 and 3 systems. Parameters such as the set speed or headway distance can be displayed independently of symbols. For instance, the headway distance can appear transiently when being set or can be embedded in an automation display and remain on-screen. This could impact the demand to process this information. Where these parameters are presented and how this affects drivers' attention will be investigated in future studies.

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Chapter III

User-Centred Design Evaluation of Symbols for Adaptive Cruise Control and Lane Keeping Assistance

ABSTRACT

Advanced driving assistance systems (ADAS) are now numerous, each relieving drivers of their responsibility for the control of different aspects of the driving task. Notably, adaptive cruise control (ACC) for longitudinal control, or lane departure prevention (LDP) and lane centring control (LCC) for lateral control, two variations of the lane-keeping assistance (LKA) system. Drivers must familiarise themselves with various symbols to correctly identify and activate the system they wish to be using and the existing standard graphical symbols for ACC and LKA are often replaced by manufacturers in favour of their own symbols. With a user-centred approach in mind, we previously conducted a workshop where drivers were invited to design their own symbols and discuss those symbols currently in-use. In the present research, we administered an online survey and analysed the responses from 328 drivers regarding different levels of knowledge about ADAS, to evaluate the usability of a selection of these symbols. Our results indicate that the standard ACC symbol would not be the most suitable of the four symbols tested, whereas, the standard LKA/LDP symbol was greatly confused with any of the four LCC symbols we tested, especially if hands were present on the symbol. Finally, drivers without prior knowledge of ADAS had more difficulties interpreting those symbols in general. Considerations for the development and evaluation of graphical symbols are discussed.

I. Introduction

According to the claims made by certain automakers in the past (e.g., Hawkins, 2017; Houser, 2018), we should already have been able to choose to be chauffeured by our cars instead of driving them—the vision for tomorrow where pressing one button will turn our cars into fully autonomous systems (SAE level 5 driving automation; ERTRAC, 2019; SAE International, 2018). Yet, the current reality is that we are still pressing a carful of buttons to activate different and mostly independent advanced driving assistance systems (ADAS) which, system-by-system, take over more control of the driving task to finally provide partially automated driving when combined (or SAE level 2 driving automation). This requires drivers to familiarise themselves with a myriad of system functionalities, controls, names, acronyms, and symbols to be able to operate their vehicles to their fullest capabilities. Symbols form an important part of how these systems are operated, as they are used in driver-vehicle interfaces (DVI), including on buttons or on displays, to replace or accompany text and facilitate mode awareness. Differentiating and recognising these symbols is therefore essential for drivers to safely operate a vehicle equipped with ADAS as steering wheels and dashboards can now be filled with buttons, and these often do not match their corresponding symbols on the instrument panel (see Perrier, 2019). In this paper, we explore the importance of symbol design, some issues with the two current ADAS defining what a level 2 partially automated system is, and report data from a survey to try and address these challenges to usability.

1. The importance of symbols

Firstly, graphical symbols are means of communication: they are used to convey complex concepts within a lesser space than a full written sentence does (Gittins, 1986; Womack, 2005). They can be easier to remember than written words (Stenberg, 2006), faster to categorise (Job et al., 1992), easier to find during a visual search (Liang et al., 2018; Ojanpää, 2006), easier to read from a fixed distance (Rettenmaier et al., 2020), and are also easier for individuals living with dyslexic problems (Kim & Wiseheart, 2017). Comprehensible symbols (aka 'icons' if presented on a computer screen) can help users retain information when learning how to use a system as compared to a text-only interface (Huang et al., 2019). Applied to vehicles equipped with ADAS, symbols can potentially reduce the need for long instructions and help drivers understand the functionality of an ADAS, even at first use. In other words, well-designed symbols can improve the usability of a system through increasing its intuitiveness [‡] (i.e., learnability; Reddy et al., 2009), memorability, and efficiency[§] (Nielsen, 1994).

The adaptive cruise control (ACC) and lane-keeping assistance (LKA) systems deal with longitudinal and lateral controls of a vehicle, respectively. ACC is "*a system which accelerates or decelerates the vehicle to automatically maintain a driver pre-set speed and driver pre-set gap distance from the vehicle in front*" (ISO 7000-2580), while LKA is a "*system to keep a vehicle between lane markings*" (ISO 7000-3128). Both have distinct standard symbols to identify them easily and quickly in any vehicle. These symbols were submitted to and validated by the committee of ISO/TC 145/SC3, in charge of graphical symbols for use on equipment, in 2004 and 2013 respectively (see **Figure 3.1**).

Figure 3.1 Standard symbols for adaptive cruise control (ACC) and lane-keeping assistance (LKA).

2. Some issues with the ACC and LKA systems

Despite these standards, there exist several reinterpretations of ACC symbols produced and used by automakers (see **Figure 3.2**), and more than 20 name variations currently in use (AAA et al., 2020). With LKA, on the other hand, the problem is two-fold: firstly, its name and symbol are frequently associated or confused with the lane departure warning (LDW) system that only alerts drivers of an imminent swerve instead of "*keeping a vehicle between lane markings*" (ISO 7000-3128). Secondly, its name and symbol are now used to describe two systems with different

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[‡] Intuitive: fast and effortless use because based on the application of prior knowledge.

[§] Efficiency: the level of productivity one reaches while using a system.

properties and behaviours (Sullivan & Flannagan, 2019). Indeed, LKA can refer to the original ‘lane departure prevention’ (LDP) system that will intermittently steer the vehicle to prevent it from crossing lane boundaries, while LKA can also refer to the more recent ‘lane centring control’ (LCC) system that will continuously use lane markings to compute a path for the vehicle to follow automatically like a rail. The end result is indeed similar: LKA systems will “*keep a vehicle between lane markings*” (ISO 7000-2580), but these two systems do not demand the same investment from drivers, because they do not have the same capabilities. LDP requires drivers to steer and will only intervene intermittently, whereas LCC can potentially entirely replace drivers in lateral control if used within its operational design domain. This should be reflected both in the symbol and the name, which is not necessarily the case as it has been shown that ‘assist’ was an ambiguous term for drivers to build a first mental model of an ADAS (Abraham et al., 2017; see also Nees, 2018; Teoh, 2020).

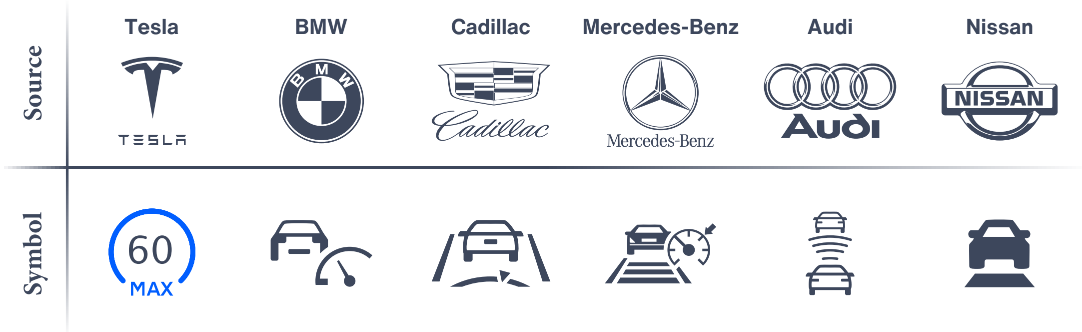


Figure 3.2 Examples of manufacturer symbols for ACC.

3. The issues with ACC and LKA symbols

The reason why manufacturers opt for designing their own symbols might be that it allows them to stand out from their competitors by bringing a new name and a new face to a product that already exists on the market while justifying this by the fact that their version of the system has different limitations than those of their competitors. Yet, this does not rule out the possibility that a symbol designed before 2004 or 2013 does not correspond exactly to what the customers need today, ADASs being more numerous and more advanced than they were then. Understandably, symbols judged appropriate by the ISO are not guaranteed to be understood nor preferred by everyone given the difficulty to represent such complex systems in a single symbol; see Sayer and Green (1988) or Payre and Diels (2019) for instance. A comparison between the method used by the ISO to produce candidate symbols and a focus group method suggests that a user-centred approach (UCD; the focus group method)—that is, considering users' need—would be more efficient and more effective to produce meaningful symbols (MacBeth et al., 2006). This same approach allowed us, for instance, to bring light on potential flaws with the current design of ACC standard symbol (Perrier et al., 2019), notably the lack of representation of the 'pre-set gap distance'.

Because the organisations designing these symbols do consider the other relevant standards that have been developed to date (Peckham, 2012), unless LDP and LCC are standardised as two distinct systems there cannot be any revision of the LKA standard symbol that would make this distinction. Symbols used alongside other symbols should be sufficiently visually distinct to not interfere with each other (Lotto et al., 1999; Silvennoinen et al., 2017), so as to avoid mode confusion (Carsten & Martens, 2019). Currently, there are risks of confusion for drivers of any vehicle equipped with both types of LKA and displaying both symbols on display (e.g., Cadillac CT6, DS 7, Ford Focus; **Figure 3.3**), or for drivers renting a vehicle equipped with an LDP when they only previously used LCC, or again for drivers trying a vehicle equipped with an LCC less capable than the one they were using before.

Figure 3.3 Symbols for LDP and LCC used next to each other in the Ford Focus 2018.

4. Solving the issues with symbols

Drivers should be confronted with the same symbol when willing to use a particular ADAS throughout their lifelong user experience with a system. And if one symbol is to be used for an ADAS, this symbol should therefore describe the system the best it can and should be understandable both for those unfamiliar with the system and those familiar with it. Having one good symbol is essential to avoid confusion. For these reasons, we previously conducted a participatory design workshop/focus group where drivers were invited to individually design their own symbols for ACC and LCC while being made aware of the existence of the conventional cruise control (CC) and LDP systems (Perrier et al., 2019). Additionally, those same drivers collectively reviewed different designs available on the market and the symbols produced specially for the workshop. The four best symbols for ACC and LCC were then selected for the present research.

The issues raised previously were addressed here during an online survey including comprehension tests for ACC and LCC symbols, and a matching test for the seven most common ADASs. Comprehension tests are used to evaluate the understandability of symbols by a target population (Carney et al., 1998) whereas matching tests are used to assess how confusing symbols would become when used alongside other symbols. The aim of this research was to point towards flaws in the current designs of ADAS symbols, potentially argue in favour of a more user-centred design approach to standardising symbols, and eventually contribute to the development of adapted standards and regulations for driving automation systems (e.g., ACEA, 2019). To that end, the research questions we addressed were:

I. Which ACC and LCC symbols are better understood by drivers?

II. Are these symbols confusing when used alongside other ADAS symbols?

III. Are there flaws with the current ADAS symbols?

II. Methods

1. Participants

Four-hundred and seven (407) people across 47 countries responded to our online survey. Of all the respondents, we excluded the ones that were ① aged less than 20 years old, ② had a driving license issued after 2017 in order to only keep drivers with approximately two years of experience, or ③ did not have a valid driving license at all. All participations presenting missing data or responses judged inappropriate were completely discarded. This lowered the total number of responses considered to three-hundred and twenty-height (328).

Female (*N* = 128), male (*N* = 197), and non-gendered (*N* = 3) respondents in our sample were not evenly represented across age. The total number of respondents by age category, regardless of gender, was roughly similar except for the 41 to 50 years old group, although the group of 51 years and older was also a much larger group than the others. More than half of the respondents had spent most of their lives in either the United Kingdom or France (54.6%).

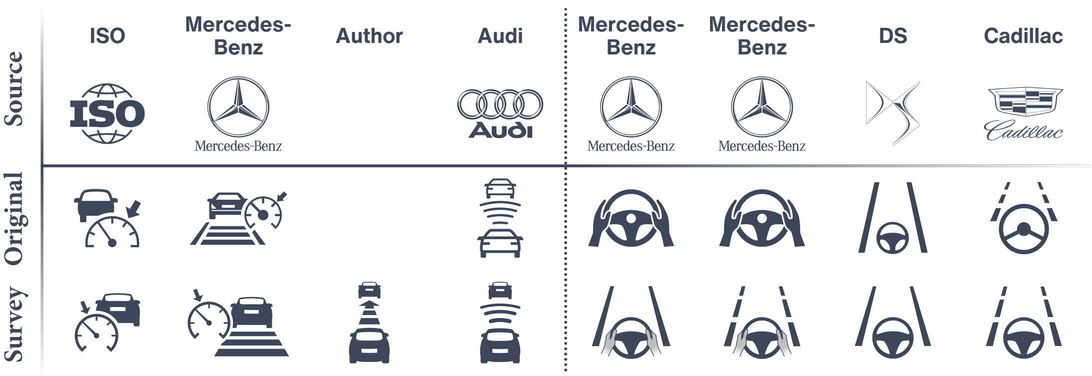
Because of a technical error that occurred at an unknown date and time after the start of the survey, an inestimable number of respondents were exposed to the same ACC and LCC symbols during the matching task, making any comparison between symbols impossible. Consequently, we preferred to remove from this analysis all respondents that completed the survey prior to when the error was detected and solved. This resulted in ninety-six (96) valid responses composed of twenty-eight (*N* = 28) female and sixty-eight (*N* = 68) male respondents for this task only.

2. Materials

Eight symbols were selected for representing ACC and LCC based on the data obtained during a participatory design workshop (Perrier et al., 2019). The four symbols judged best for each system were redesigned to take into account certain elements of feedback and their overall appearance harmonised (**Table 3.1**). Notably, the arrow above the speedometer was moved to the left side as it confused drivers when placed on the right side (1st and 2nd ACC symbol). For the 2nd ACC symbol

(Mercedes-Benz, 2020, p. 224) the lane markings were removed as ACC does not rely on road markings and they cluttered the symbol. For the 3rd ACC symbol, an ego vehicle was added to better illustrate the notion of pre-set gap distance. The 1st and 2nd LCC symbols were mostly inspired by the Mercedes-Benz symbol (Mercedes-Benz, 2020, p. 221). The 4th ACC symbol (Audi, 2020, p. 10), as well as the 3rd and 4th LCC symbols (Cadillac, 2020; DS Automobiles, 2010), were only graphically harmonised with the others.

Table 3.1 Sources for the symbols evaluated in the survey. Left: ACC symbols. Right: LCC symbols.



3. Design & procedure

The online survey was designed and administered on Qualtrics' software (Qualtrics, Provo, UT). To reach a wider audience, the survey was made available in three languages: English (British), French (Metropolitan), and Spanish (Mexican). It was advertised on social media (Facebook, Twitter, LinkedIn), via newsletters**, and word-of-mouth. It was described as targeted to drivers who were unfamiliar with automated vehicles. No compensation was promised to respondents.

Participants were first invited to choose their preferred language and invited to use a tablet or laptop had they been using a mobile phone.

** ① Connected Automated Driving (CAD) Europe; ② European New Car Assessment Programme (Euro NCAP); ③ European Transport Safety Council (ETSC); ④ Institute for Transport Studies; ⑤ School of Earth and Environment, University of Leeds.

Before starting the survey, participants read a brief introduction to the research context, purpose, and their role, before giving their consent to participate and proceed to the survey.

4. Demographics & driving experience

The first part of the survey covered demographics and driving experience variables. See **Appendix 3.1** for a complete list of these questions. We asked what general knowledge about ADAS respondents had. They had to indicate whether: ① they did not know what ADAS were, ② they had only heard of them, ③ they had seen demonstrative videos, ④ they had seen someone using them, ⑤ they had used them before, or whether ⑥ their occupation involved these systems. This factor could be determinant in how respondents would interpret the symbols. We also asked respondents whether they had any background in human factors of automotive or other fields, graphic design, industrial design or other design fields, or professional driving. Anyone with enough knowledge of the human factors in the automotive industry may be more likely to recognise the symbols accurately. Similarly, those in visual or graphic design may have an advantage in interpreting symbols generally.

5. Comprehension test

At the start of the survey, respondents were asked to carefully read all instructions before completing each section. Respondents were randomly assigned one of four symbols for each system. This would determine which symbol for ACC and LCC they would see during the survey. This was done to avoid learning effects between symbols and question order bias.

The context in which the first symbol (ACC) would appear was explained along with an image showing what the interior of a car equipped with ADAS could look like to facilitate immersion in the task. A very short explanation of what ADAS are and the descriptions of two systems were given (i.e., Obstacle Detection and Automatic Parking). However, the names were not given.

If respondents pressed one button with ACC's symbol on it, they were asked to ① name or describe the elements contained in the symbol and to ② describe what sort of driving assistance this symbol would represent, explaining how it could function and which aspects of driving would be assisted. The first question was introduced to analyse how the content of each symbol was perceived. The second question was designed to assess how those symbols were interpreted. The same procedure was repeated for LCC.

Table 3.2 ADAS used during the matching test, their recreated ISO symbol (except LCC) and their description.

System	Acronym	Symbol	Description
Forward Collision Warning	FCW		Alerts drivers of an impending collision with a slower moving or stationary vehicle in the front.
Blind Spot Monitoring	BSM		Warns drivers of vehicles driving in their blind spots when using the turn signals.
Lane Departure Warning	LDW		Alerts drivers if their vehicle is drifting out of a lane.
Cruise Control	CC		Maintains the vehicle at drivers' set speed.
Adaptive Cruise Control	ACC		Automatically speeds up and slows down drivers' vehicle to keep a set speed and following distance relative to the vehicle ahead.
Lane Departure Prevention	LDP		Intermittently steers driver's vehicle back into their lane if the system detects it's drifting out of it.
Lane Centring Control	LCC		Continuously steers drivers' vehicle to keep it in their intended lane.

6. Matching test

Seven symbols and seven descriptions were shown to participants (see **Table 3.2**). Their task was to associate (or 'match') each symbol to the system description they judged was the most representative. This procedure was designed to assess the confusion that could exist when a symbol is introduced in an eco-system of other symbols that represent different functionalities.

Each system could be matched with more than one symbol and all symbols had to be matched with at least one system to be able to proceed with the survey (**Figure 3.4**). This last requirement was introduced to ensure that respondents were not simply trying to complete the survey more quickly. None of the system names was disclosed to the respondents and the symbols for ACC and LCC were changed according to what symbols were shown during the recognition task. In preparation for this test, respondents were first trained to drag-and-drop with only one symbol and one system absent from the test (the ABS system).

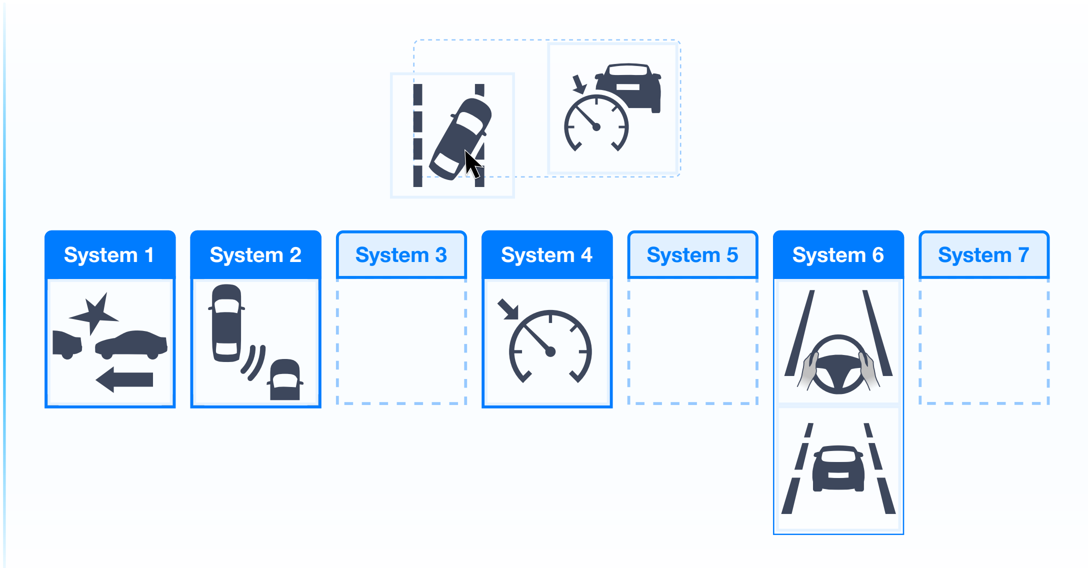


Figure 3.4 Representation of the drag-and-drop task for the matching test.

Finally, respondents were asked to indicate whether they had already seen either of the seven symbols before (the names were then displayed). They were thanked and invited to share the study with their network via their social media accounts.

7. Data analysis

The goal of this study was to assess how several symbols compared in a comprehension test—do these symbols communicate the right message—and a matching test—do these symbols communicate the right message embedded within a set of symbols or are they confusing?

To answer the first question, we split the comprehension test into two analyses. Firstly, we compared each respondent's description of each symbol to a definition and scored it to reflect its fit to the intended meaning. We then used these scores to run ordinal logistic regressions. Secondly, we classified each response to indicate what type of system they were currently describing. Finally, for the matching task, the percentage of accuracy was computed for each symbol and we analysed whether the symbols were matched accurately or not using binary logistic regressions.

A. Scoring of comprehension tests

Table 3.3 Definitions of the adaptive cruise control (ACC) and lane centring control (LCC) systems. Bold: major informational elements. Italic: minor informational elements.

System	Description
ACC	My car **accelerates** automatically to maintain a *set speed*. My car detects the **traffic in front**. My car **decelerates** automatically to maintain a set *following distance*.
LCC	My car **steers** automatically to follow/stay in its current lane of travel.

Following the method used by (Campbell, Hoffmeister, et al., 2004), accuracy was assessed by comparing each response to a definition specific to each system (see **Table 3.3**). For ACC, controlling speed and being aware of preceding traffic while doing so were judged to be major informational elements as they describe what the system does to contribute to the dynamic driving task. The set speed and set following distance were considered relevant but minor elements as they are only quantified measures related to the major elements and only become relevant on an operational level, that is, after a driver took the decision to activate their ACC system. For LCC, steering was judged major and the purpose of staying in the current lane minor yet relevant as it differentiates the system from an LDP or an LDW. The responses were scored on a scale from 1 to 9 based on their similarity to the formal definition (see **Table 3.4**).

Table 3.4 The rating scale for scoring respondents' responses.

Score	Description
1	The response **matches** the intended meaning of the symbol **exactly**.
2	The response **captures all major** informational elements of the intended meaning of the symbol but is **missing one** or **more minor** informational elements.
3	The response **captures some** of the **intended meaning** of the symbol, but it is **missing one** or **more major** informational elements.
4	The response does not match the intended meaning of the symbol, but it **captures some major** or **minor** informational elements.
5	The response does not match the intended meaning of the symbol, but it is **somewhat relevant**.
6	Participant's response is **in no way relevant** to the intended meaning of the symbol.
7	The participant indicated he/she **did not understand** the symbol.
8	No answer.
9	**Critical confusions**, the participant perceived the message to **convey a potentially unsafe action** or the response given is the **opposite** of the **intended meaning**.

B. ADAS interpretations of symbols

Responses were classified as describing one of several systems, real or made-up by respondents, to better represent the nuances introduced in their interpretations (**Appendix 3.2**). These nuances could inform us of what type of active safety systems drivers imagine their driving assistance systems to be: alerts, vehicle adjustment, or active control (see SAE International, 2018) and what aspects of the driving task these systems would support.

C. Analysis of comprehension tests

We conducted ordered logistic regressions to assess the comprehension scores for each of the ACC and LCC questions. We used the *ordinal* package version 2019.12.10 for the R software (R Core Team, 2020). The *sure* package version 0.2. 0 (Greenwell et al., 2017) was used to evaluate the goodness-of-fit of the link functions (i.e., logit) by means of the Kolmogorov-Smirnov test, as well as for plotting the Q-Q plots of the surrogate residuals (Greenwell et al., 2018); this latter step led us to remove one respondent judged as an outlier for the regression on ACC comprehension scores and two respondents for the regression on LCC comprehension scores. All significance thresholds were at 95% ($\alpha = .05$).

Ordered logistic regression for ACC

For the ACC model, we used custom-coded contrasts for the effect of the symbols, reversed Helmert-coded contrasts for the effect of ADAS knowledge, backward difference-coded contrasts for the effect of familiarity with CC and ACC ISO symbols. The interaction terms for the effects of symbols and familiarity were also modelled.

For the effect of symbols, the first contrast (*Symbol* Ψ_1) compares the scores for symbols 1 plus 2 to the scores for symbols 3 plus 4. We judged this comparison interesting as symbol 2 is an extension of symbol 1, and symbols 3 and 4 are also similar in their semiology. The second contrast (*Symbol* Ψ_2) compares symbol 1 to symbol 2, while the third contrast (*Symbol* Ψ_3) compares symbol 3 to symbol 4.

For the effect of general knowledge on ADAS, we used a family of reverse Helmert contrast (*Knowledge* $\Psi_{1\text{-}5}$). Each contrast compares one level of a factor to all previous levels and tells us whether each increment has an effect on the dependent variable. We hypothesised that knowledge would have a positive and cumulative effect on the scores, therefore these comparisons were an appropriate choice.

For the effect of familiarity with the ISO symbols of CC and ACC, we used a pair of backward difference contrast (*Familiarity* $\Psi_{1\text{-}2}$). Each contrast compares one level of a factor to the previous adjacent level only. This coding is useful to compare the levels of a nominal or ordinal factor. It is reasonable to hypothesise that the distance between *'CC'* and *'ACC'*

(*Familiarity* Ψ_2) was shorter than the distance between *'none'* and *'CC'* (*Familiarity* Ψ_1) and therefore we judged it was a better solution than Helmert contrasts. Note also that no respondent knew the ACC symbol without also knowing CC symbol, hence the choice to group these two factors together to form an ordinal factor.

Finally, the interaction terms between symbols and symbol familiarity were also modelled (*Symbol Ψ* × *Familiarity Ψ*).

Ordered logistic regression for LCC

For the LCC model, we decomposed the effect of symbols into two simple-coded contrasts and their interaction. Given the similarity of the elements composing all four variants and the feedback gathered in our previous research, the first contrast (*Hands Ψ*) tested the effect of hands' representation on the symbols (*handed – handless*) while the second contrast (*Lines Ψ*) tested the effect of the lines' design on the symbols (*continuous – dashed*). Hands being depicted on the symbols was important for drivers if they were to keep theirs on the steering wheel, while continuous lines seemed to indicate a more robust system (Perrier et al., 2019). The interaction between these elements was modelled as well (*Hands Ψ* × *Lines Ψ*).

We used the same reversed Helmert-coded contrasts used for ACC for the effect of general knowledge about ADAS (*Knowledge* $\Psi_{1\text{–}5}$), and three simple-coded contrasts for the effects of familiarity with LDW, LKA and LCC symbols (*Familiarity LDW, Familiarity LKA, Familiarity LCC*). The interaction terms between the contrasts for the symbols (*Hands Ψ*, *Lines Ψ*, *Hands Ψ* × *Lines Ψ*) and familiarity with LKA symbol (*Familiarity LKA*) were also modelled.

D. Analysis of matching task

To assess the accuracy of matching for the ACC and LCC symbols we conducted two binary logistic regressions, using the R software (R Core Team, 2020). Given the limited number of responses for this part of the survey, we only modelled the fixed effects of symbols, ADAS knowledge and symbols familiarity. Moreover, to appropriately account for the effect of general knowledge about ADAS we grouped the six levels of knowledge by pairs (i.e., 1+2, 3+4, and 5+6) and coded this factor as a pair of backward difference contrasts to compare each level to the previous adjacent level only. An analysis of standardised residuals did not indicate influential data and no multicollinearity was found between factors for any model.

III. Results

1. Comprehension tests

A. *Adaptive Cruise Control*

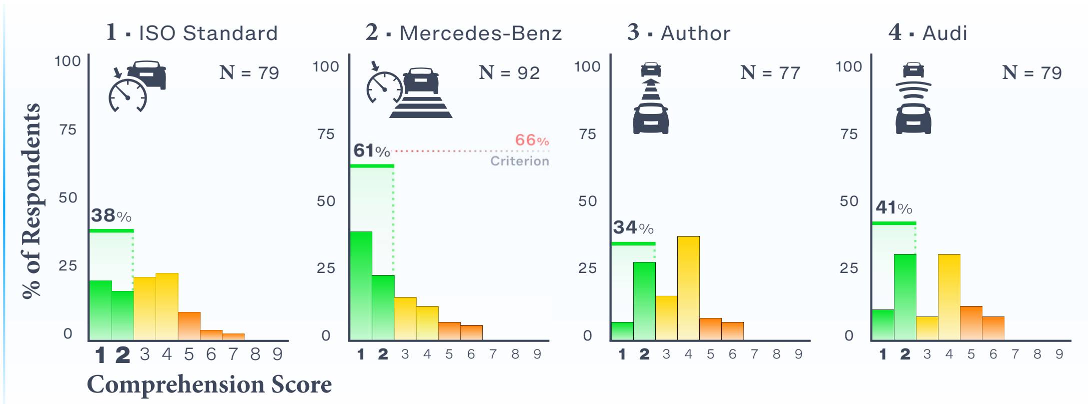


Figure 3.5 Percentage of responses for each score level of each ACC symbol. Percentage of high scores are displayed above scores 1 and 2. Green: high scores. Yellow: low scores. Orange: no response. Red: critical confusions.

Figure 3.5 presents the overall results for the comprehension tests of each ACC symbol. Following Campbell et al. (2007), score levels can be grouped in four categories of responses: *high scores* (green), *low scores* (yellow), *none* (orange), and *critical confusions* (red). To be judged good enough a symbol should obtain a *high score* of at least 66% (Campbell, Richman, et al., 2004). On this criterion, only the second symbol is near passing the evaluation. The ISO-inspired symbol (symbol 1), despite having lower scores than the second symbol, seems to have a more even spread of its scores and more 1s than symbols 3 and 4. These latter symbols obtained a very similar pattern of scores. **Table 3.5** presents the results of the ordered logistic regression we ran on ACC scores ($N = 327$).

Table 3.5 Fixed effects from the ordered logit regression model on scores for ACC. Significant results noted * ($p < .05$).

Coefficients	β	*SE* β	OR (e^{β})	CI 95%	Wald's *z*	*p*	
Symbol Ψ_1	−0.79	(0.21)	0.46	0.3 – 0.68	−3.83	< .001	*
Symbol Ψ_2	0.72	(0.3)	2.06	1.16 – 3.69	2.45	.01	*
Symbol Ψ_3	0.02	(0.28)	1.02	0.59 – 1.78	0.07	.95	
Knowledge Ψ_1	1.71	(0.51)	5.54	2.07 – 15.14	3.38	< .001	*
Knowledge Ψ_2	1.29	(0.5)	3.63	1.36 – 9.81	2.57	.01	*
Knowledge Ψ_3	0.9	(0.71)	2.45	0.61 – 9.94	1.26	.21	
Knowledge Ψ_4	1.01	(0.73)	2.75	0.66 – 11.47	1.39	.16	
Knowledge Ψ_5	3.09	(0.84)	22.01	4.29 – 115.68	3.68	< .001	*
Familiarity Ψ_1	0.42	(0.26)	1.52	0.9 – 2.55	1.57	.12	
Familiarity Ψ_2	0.57	(0.28)	1.77	1.02 – 3.11	2.02	.04	*
Symbol Ψ_1 × Familiarity Ψ_1	−0.92	(0.51)	0.4	0.15 – 1.08	−1.8	.07	
Symbol Ψ_2 × Familiarity Ψ_1	2.39	(0.76)	10.95	2.5 – 48.62	3.17	< .001	*
Symbol Ψ_3 × Familiarity Ψ_1	1	(0.7)	2.73	0.69 – 10.87	1.43	.15	
Symbol Ψ_1 × Familiarity Ψ_2	−0.85	(0.5)	0.43	0.16 – 1.15	−1.69	.09	
Symbol Ψ_2 × Familiarity Ψ_2	1.71	(0.75)	5.54	1.29 – 24.03	2.3	.02	*
Symbol Ψ_3 × Familiarity Ψ_2	0.86	(0.7)	2.36	0.59 – 9.41	1.22	.22	

a. Effect of symbols

The first contrast (*Symbol* Ψ_1) tells us that the first pair of symbols (1 plus 2) had significantly higher scores than the second pair of symbols (3 plus 4): 49.5% versus 37.5%. The second contrast (*Symbol* Ψ_2) tells us that symbol 2 (61%) was scored significantly higher than symbol 1 (38%). Finally, the third contrast (*Symbol* Ψ_3) was not significant, which implies that the difference between symbols 3 and 4 was not significant (34% vs 41%). To conclude on this family of contrasts, the 2nd symbol (modified Mercedes-Benz symbol) was statistically better recognised than the current standard symbol and seemingly more than the two other symbols.

b. Effect of general knowledge about ADAS

The first contrast (*Knowledge* Ψ_1) indicates that respondents who had only heard of ADAS before produced significantly better descriptions of the symbols than the respondents who reported they did not know what ADAS were. The second contrast (*Knowledge* Ψ_2) also indicates that the viewing of demonstrative videos had a significant impact on comprehension scores overall. The third contrast (*Knowledge* Ψ_3) and the fourth contrast (*Knowledge* Ψ_4) were not significant, indicating that having seen someone using ADAS before or having used ADAS before did not result in a significant effect on respondents' responses. Working on ADAS (*Knowledge* Ψ_5), however, was reported as having a significant effect on symbol recognition.

To summarise, it appears that the general level of knowledge on ADAS has a certain positive effect on how accurately drivers can describe the meaning of a symbol. This suggests that drivers naïve to ADASs may have difficulties deducing the meaning of these symbols. Finally, it appears that having seen someone using ADAS or having used ADAS would provide no additional advantage for understanding a symbol's meaning.

c. Effect of familiarity with CC and ACC symbols

The first contrast (*Familiarity* Ψ_1) was not significant, signifying that simply knowing the ISO symbol for CC did not lead to greater recognition of the ACC symbols. The second contrast (*Familiarity* Ψ_2), however, was significant, suggesting that if a respondent knew ACC's ISO symbol, they tended to produce symbol descriptions that were overall scored higher than the other respondents. It is a surprise that knowing CC's symbol would not benefit respondents in their response to the first two symbols as both incorporate this former symbol. However, interaction effects may further explain this.

d. Interaction effects

It was possible that knowing the standard symbols for CC and ACC would affect symbols recognition differently and was therefore modelled in the regression. Firstly, the second and fifth interaction terms (*Symbol* Ψ_2 × *Familiarity* Ψ_1 & *Symbol* Ψ_2 × *Familiarity* Ψ_2) were significant, suggesting that the benefit of knowing CC symbol or both CC and ACC symbols differed between the first and second symbols (i.e., ISO and Mercedes-Benz symbols). More specifically, knowing the standard symbols for CC and ACC had more influence on the responses given for the second symbol than for the first symbol (the ISO symbol). This can be interpreted as the second symbol having a design that reminded respondents of more details about ACC, given they already knew the standard symbol, and thus, probably, the system itself.

e. Summary of the ordered logistic regression

To conclude this first analysis, the second symbol was the most recognised by drivers, followed by the first ISO symbol. Having heard of ADAS before helped the most naïve drivers to interpret the symbols they were presented, while experts in the domain were also better at interpreting the same symbols. Evidently, knowing the standard ACC symbol beforehand was an advantage for drivers in interpreting the symbols, and more so if they were presented the second symbol (modified Mercedes-Benz symbol).

f. Symbols interpretation

To understand why each symbol was scored the way it was and detect potential flaws in symbols' design, this second part of the analysis considered how drivers interpreted the ACC and LCC symbols. That is, which ADAS, real or not, they would expect these symbols to represent. Some interpretations were isolated cases or did not correspond to anything close to an ADAS and were all grouped under the category 'other'.

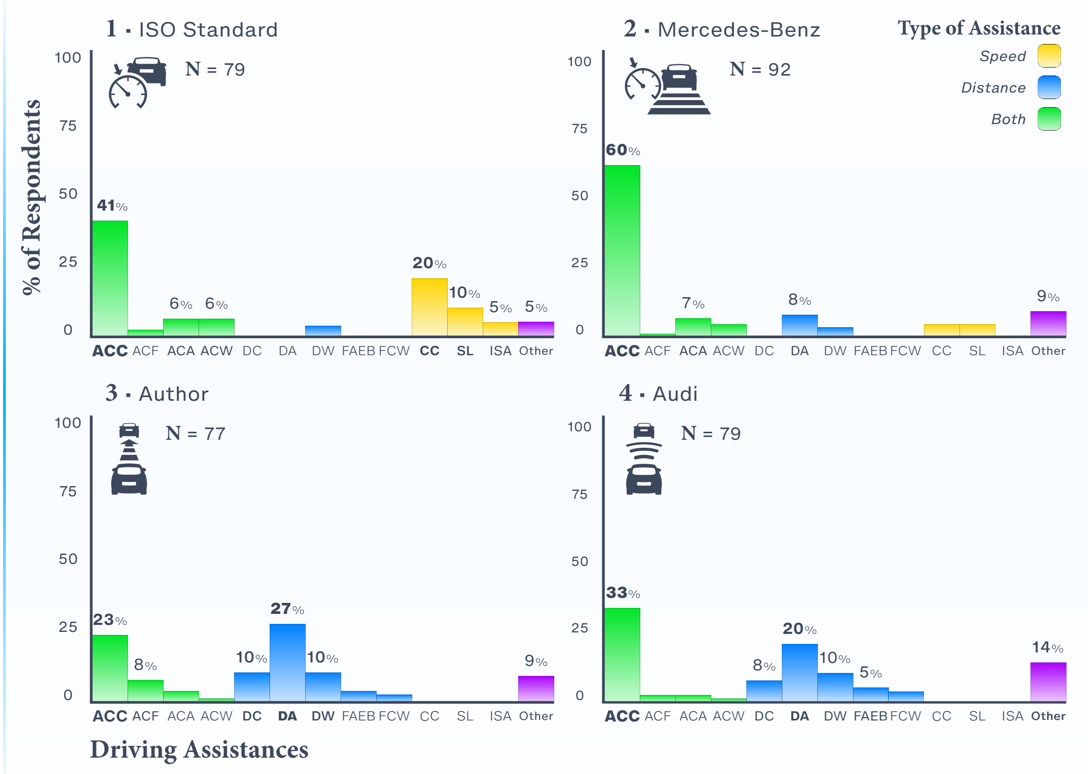


Figure 3.6 Most notable interpretations of each ACC symbol. Green: systems combining speed and distance assistance. Blue: systems assisting with headway distance. Yellow: systems assisting with speed. Purple: systems that could not be classified. Refer to **Appendix 3.2** for an explanation of each acronym.

Figure 3.6 shows how each system was described as an ADAS and what major elements were mostly evoked by respondents due to their design. Only the percentages over 5% were included in the figures. Firstly, the ISO symbol was the most interpreted as a simple speed assistance system (total: 36% of respondents). The second symbol was rarely interpreted as simple distance assistance or a simple speed assistance system overall. Of these two symbols, it seems that the ISO symbol was good at representing how speed is assisted by the system but failed to help drivers easily understand how lead vehicles are also taken into account to regulate their speed and their headway distance. Secondly, the third and fourth symbols received similar interpretations: they were less often described as both speed and distance assistance systems than the first two symbols and were interpreted as simple distance assistance systems amongst 45-50% of respondents. The third symbol was the most described as an ‘(adaptive) car following’ system (ACF = 8%), most likely due to its arrow not being interpreted as the ego car’s movement but as pointing to the lead car. Finally, the fourth symbol had the most unclassified interpretations. Some of these interpretations were still somewhat relevant, such as an indicator of the speed limit or the current headway distance, while some were relevant but too broad or inaccurate to be classified in the most common interpretations; for instance, some respondents interpreted the symbols as ‘speed control’, ‘automated driving’, ‘cooperative cruise control’, or again ‘dynamic cruise control’ (DCC; see **Appendix 3.2**). Nothing can be concluded from these isolated cases.

B. Lane Centring Control

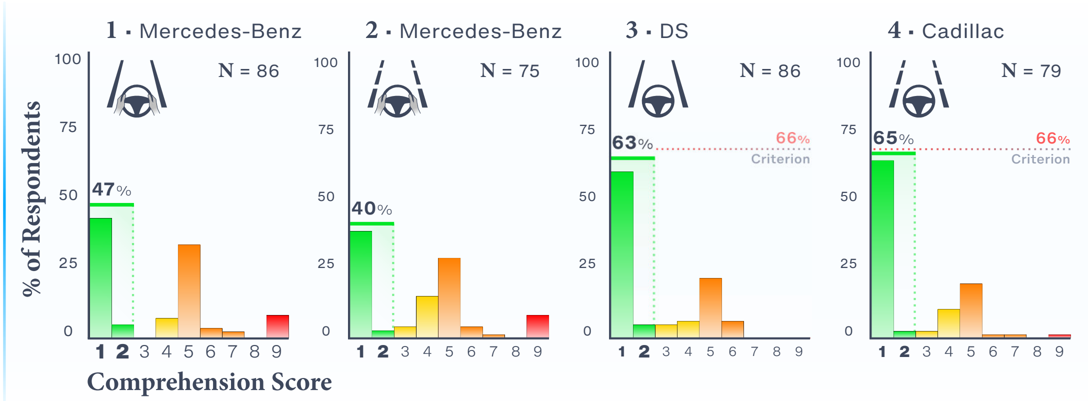


Figure 3.7 Percentage of responses for each score level of each LCC symbol. Percentage of high scores are displayed above scores 1 and 2. Green: high scores. Yellow: low scores. Orange: no response. Red: critical confusions.

Figure 3.7 presents the overall results for each LCC symbol (*N* = 326). Only based on the 66%-criterion, the third and fourth symbols would be near acceptable choices for representing LCC in a vehicle equipped with ADAS. Interestingly, these are the two symbols not depicting hands on the steering wheel. **Table 3.6** presents the results for the ordered logistic regression we ran on the comprehension scores.

Table 3.6 Fixed effects from the ordered logit regression model on scores for LCC. Significant results noted * (p < .05).

Coefficients	β	*SE* β	OR (e^{β})	CI 95%	Wald's *z*	*p*	
Hands Ψ	1.01	(0.23)	2.75	1.75 – 4.36	4.33	< .001	*
Lines Ψ	−0.02	(0.23)	0.98	0.62 – 1.53	−0.1	.92	
Hands × Lines Ψ	0.12	(0.46)	1.13	0.46 – 2.79	0.27	.79	
Knowledge $Ψ_1$	1.33	(0.51)	3.76	1.39 – 10.3	2.61	.01	*
Knowledge $Ψ_2$	0.48	(0.5)	1.61	0.61 – 4.32	0.95	.34	
Knowledge $Ψ_3$	0.26	(0.72)	1.29	0.32 – 5.42	0.36	.72	
Knowledge $Ψ_4$	−0.19	(0.74)	0.83	0.19 – 3.59	−0.25	.80	
Knowledge $Ψ_5$	1.93	(0.92)	6.87	1.16 – 43.08	2.1	.04	*
Familiarity LDW Ψ	−0.12	(0.32)	0.89	0.48 – 1.68	−0.36	.72	
Familiarity LKA Ψ	0.18	(0.28)	1.2	0.7 – 2.07	0.65	.52	
Familiarity LCC Ψ	0.17	(0.33)	1.19	0.63 – 2.26	0.52	.60	
Hands × Fam. LKA Ψ	−0.13	(0.46)	0.88	0.36 – 2.19	−0.28	.78	
Lines × Fam. LKA Ψ	−0.91	(0.46)	0.4	0.16 – 0.99	−1.98	.05	*
Interaction × Fam. LKA Ψ	1.33	(0.92)	3.8	0.62 – 23.36	1.44	.15	

a. Effect of LCC symbols

The first contrast (*Hands Ψ*) indicates a significant difference between the *handed* and *handless* symbols, these latter being associated with more accurate descriptions than the handed ones. Lines design (*Lines Ψ*) did not have a significant effect on symbols recognisability and no interaction effect was observed (*Hands × Lines Ψ*).

b. Effect of general knowledge about ADAS

The first contrast (*Knowledge* $Ψ_1$) indicates that respondents who had only heard of ADAS produced significantly better descriptions of the symbols than respondents who reported they did not know what ADAS were. The fifth contrast (*Knowledge* $Ψ_5$) also indicated a significant difference when comparing the drivers who were working on ADAS to the other drivers. None of the other comparisons was significant. This suggests again that at least having heard of ADAS before helped drivers understand the symbols better. Unless a person worked on ADAS and would therefore likely have a better understanding of what these systems are and how they operate, there were no notable benefits of being exposed to ADAS. This could signify that these symbols are a good fit for relatively any type of drivers except for those who had never heard of ADAS before and are confronted to them for the first time. Consistently with what was found for ACC, it might be a difficult task for a naïve driver to guess first-hand what a vehicle equipped with ADAS can do for them or not.

c. Effects of familiarity with LDW, LKA, or LCC symbols

Respondents' familiarity with the LDW ISO symbol (*Familiarity LDW Ψ*), LKA ISO symbol (*Familiarity LKA Ψ*) or LCC symbol (*Familiarity LCC Ψ*) was not associated with greater symbols recognition. According to our data and statistical model, prior familiarity with lane assistance systems' symbols was neither an advantage nor a disadvantage for interpreting the symbols evaluated in this survey.

d. Interaction effects

To assess whether knowing the standard LKA symbol would affect respondents' interpretation of symbols' elements differently we modelled the corresponding interaction in our regression. Only the interaction between the lines design and the familiarity with LKA symbol (*Lines × Familiarity LKA Ψ*) was significant. This suggests that the continuous lines on LCC symbols were more often associated with high comprehension scores. This would be consistent with what was suggested by drivers in the focus group we conducted (Perrier et al., 2019), that continuous lane markings on the road should not be encroached by drivers, and that consequently a symbol depicting continuous lines could be associated with a more stable system than a symbol with dashed lines. In this study, drivers knowing LKA's ISO symbol (which presents dashed lines) might have been helped, knowingly or not, by the continuous lines and produced more accurate descriptions of LCC.

e. Summary of the ordered logistic regression

While the design of the lines had a mitigated effect in these symbols' interpretation, the absence of hands was apparently critical for drivers to produce more accurate descriptions of LCC. This effect could be due to LDP being more common in our vehicles today than LCC, and therefore knowing LDP might have pushed drivers to interpret the hands as a system that requires driver supervision. However, this might also be because having hands on the symbol is interpreted as the driver being in control, regardless of whether one knows what LDP is. Finally, similar to what was found for the ACC symbols, naïve drivers produced less accurate descriptions of LCC symbols, while drivers working on ADAS were more accurate than the rest of drivers.

f. Symbols interpretation

Firstly, the *handed* symbols (1 and 2) were the least interpreted as lane centring systems and the only ones interpreted as take-over requests or as indicators of manual driving (**Figure 3.8**). This could be consistent with what was found in the comprehension tests, this suggests that hands communicate a certain dependence of the system on the driver. Most LCC systems require drivers to keep their hands on the steering wheel during operation and representing hands on the symbol is a way of communicating that need of supervision from the driver to the driver.

Secondly, the *dashed* lines symbols were the most interpreted as LDP. As mentioned previously, it was suggested by drivers that dashed lines seem to indicate a more permissive lane assistance system, with continuous lines being used to contraindicate crossing them on real roads. There seems to be an interaction between hands and lines design, which could be interpreted as if dashed lines and hands on the same symbol would indicate the least robust LCC system. However, note that this is only a descriptive analysis.

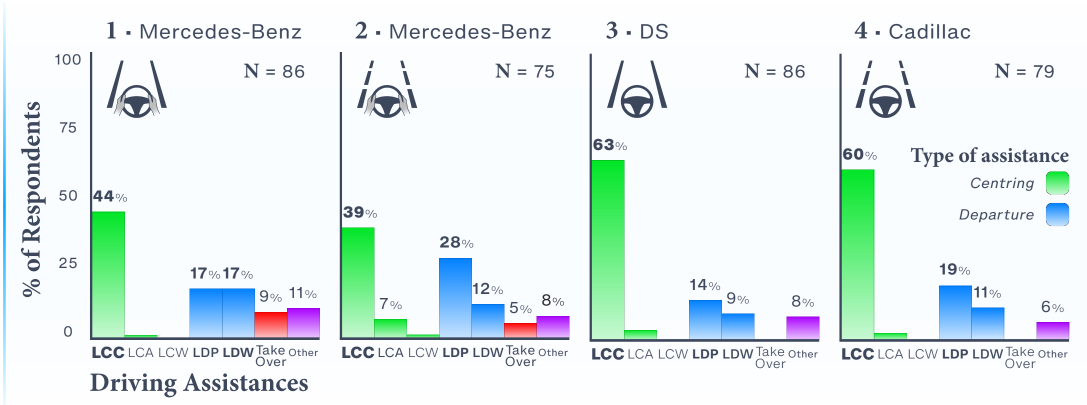


Figure 3.8 Most notable interpretations of each LCC symbol. Green: systems with a focus on lane following. Blue: systems with a focus on lane departure. Purple: interpretations opposite to the actual meaning. Red: systems that could not be classified. Refer to **Appendix 3.2** for an explanation of each acronym.

2. Matching test

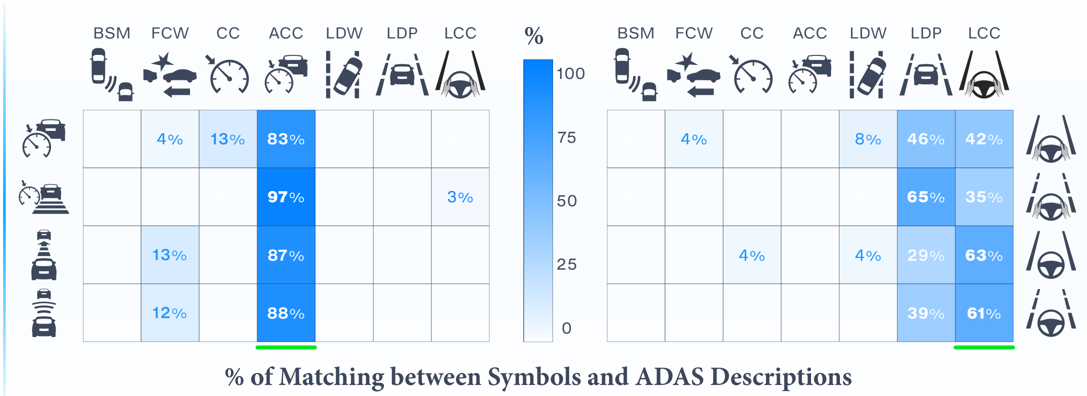


Figure 3.9 Percentage of matching between ACC and LCC symbols and each ADAS description.

The last part of the survey was designed to analyse how a symbol would become confusing when embedded within an ecosystem of other ADAS symbols. Respondents were therefore presented seven symbols and seven ADAS descriptions and were asked to match each symbol to at least one ADAS description. **Figure 3.9** presents the percentage of ACC (left) and LCC symbols (right) that were matched which each system description. Please see **Table 3.2** (p. 60) for the meaning of each acronym and symbol displayed on top of **Figure 3.9**. Please also note that percentages of 3-4% represent only one individual.

A. *Adaptive Cruise Control*

The binary logistic regression (**Table 3.7**) was modelled on the accuracy, that is, the correct association between ACC symbols and the ACC system. The first contrast (*Symbol* Ψ_1) comparing symbols 1 plus 2 (90%) to symbols 3 plus 4 (87.5%) was not significant. The second contrast (*Symbol* Ψ_2) showed that there was a significant difference between symbols 1 (83%) and 2 (97%). Finally, there was a trend advantage of familiarity with both CC and ACC symbols (*Familiarity* Ψ_2).

Looking at the matrix of percentages in **Figure 3.9**, the ISO symbol was the only one associated with CC (13%). On the other hand, symbols 3 and 4 had the highest incidents of association with FCW (12-13%). These numbers indicate that there was little confusion between all ADAS, although the second ACC symbol was most frequently correctly identified.

Table 3.7 Results of binary logistic regression for ACC. * ($p < .05$).

Coefficients	β	*SE* β	OR (e^{β})	CI 95%	Wald's *z*	*p*	
(Intercept)	2.53	(0.47)	12.49	5.61 – 37.03	5.38	< .001	*
Symbol Ψ_1	−0.21	(0.8)	0.81	0.14 – 3.84	−0.26	.79	
Symbol Ψ_2	2.52	(1.24)	12.45	1.43 – 283.86	2.03	.04	*
Symbol Ψ_3	−0.23	(1.02)	0.79	0.09 – 5.81	−0.23	.82	
Knowledge Ψ_1	0.77	(1.07)	2.17	0.27 – 21.68	0.72	.47	
Knowledge Ψ_2	−0.73	(0.95)	0.48	0.07 – 2.99	−0.77	.44	
Familiarity Ψ_1	0.38	(0.86)	1.46	0.26 – 8.29	0.44	.66	
Familiarity Ψ_2	2.12	(1.13)	8.3	0.98 – 95.86	1.87	.06	

B. *Lane Centring Control*

The only significant comparison in this binary logistic regression (**Table 3.8**) was the one comparing the effect of having hands present on the symbols or not (*Hands* Ψ). The symbols with hands (38.5%) were less correctly associated with LCC than the symbols without hands (62%). As shown in **Figure 3.9**, symbols with hands were more often associated with

LDP (55.5%) than their counterparts (34%), as also suggested by the interpretations during the comprehension test (**Figure 3.8**). The least confusing symbols were consequently the handless symbols, yet there was still a general level of confusion between the symbols for LDP and LCC that should not be neglected.

Table 3.8 Results of binary logistic regression for LCC. * ($p < .05$).

Coefficients	β	*SE* β	OR (e^{β})	CI 95%	*Wald's z*	*p*	
(Intercept)	0.15	(0.32)	1.16	0.63 – 2.19	0.47	0.64	
Hands Ψ	0.91	(0.43)	2.49	1.09 – 5.86	2.13	0.03	*
Lines Ψ	−0.12	(0.47)	0.88	0.35 – 2.21	−0.26	0.79	
Hands × Lines Ψ	0.29	(0.88)	1.33	0.24 – 7.65	0.33	0.74	
Knowledge Ψ_1	−0.01	(0.64)	0.99	0.28 – 3.51	−0.02	0.99	
Knowledge Ψ_2	0.07	(0.64)	1.07	0.31 – 3.82	0.11	0.91	
Familiarity LDW Ψ	0.01	(0.58)	1.01	0.32 – 3.13	0.02	0.98	
Familiarity LKA Ψ	−0.04	(0.56)	0.96	0.31 – 2.91	−0.07	0.94	
Familiarity LCC Ψ	0.48	(0.67)	1.62	0.44 – 6.21	0.72	0.47	

IV. Discussion

The number of symbols and name variants present in today's vehicles for the adaptive cruise control (ACC) and lane centring control (LCC) systems is a potential threat to drivers' safety and experience. Because the involvement of drivers in the design process of these symbol variants is unclear, we previously undertook a user-centred design (UCD) approach and invited drivers to a focus group to produce individually their own symbols for ACC and LCC, and then review collectively these symbols and the symbols available on the market (Perrier et al., 2019). The objective of the present study was to seek drivers' contribution in evaluating two sets of four symbols that received the greatest interest in the focus group, thus involving the potential users of these symbols in order to raise recommendations for the design and use of ADAS symbols.

In an online survey, we gathered and analysed data to try and answer three questions:

I. Which ACC and LCC symbols are better understood by drivers?
II. Are these symbols confusing when used alongside other ADAS symbols?
III. Are there flaws with the current ADAS symbols?

1. Which symbols were better understood by drivers?

ADAS symbols are used for indicating system status, but also participate in forming drivers' mental models of a system (Jung & Myung, 2006). Yet, our data suggest that naïve drivers had more difficulties guessing the meaning of symbols than people with at least some knowledge of what ADAS are. Having experienced ADAS was apparently not significantly advantageous to interpret those symbols, while drivers whose work involved ADAS were more accurate in their interpretation of ACC and LCC symbols. This supports the importance of designing intuitive symbols and providing appropriate information and training to drivers willing to use a vehicle equipped with ADAS. To illustrate, about 25% of Dutch customers did not receive any information about their ACC or LKA systems from their dealer when acquiring their vehicle (Boelhouwer et al., 2020), representing as much as 25% drivers potentially lacking such minimum level of knowledge to easily recognise ADAS symbols.

Of the four symbols evaluated for ACC, the one inspired by the standard ISO symbol (1st symbol) was the one most interpreted as simple speed assistance such as cruise control (CC), intelligent speed assistance (ISA), or speed limiter. Thus, the way of communicating how speed is affected by the presence of a lead vehicle is not entirely effective: the car on the symbol was sometimes interpreted as the ego-vehicle itself while the arrow—symbolising the target speed of ACC—being shifted beyond the needle—symbolising the current travel speed—was too subtle of a detail. However, an increased gap between the arrow and the needle as seen on the original standard symbol (**Figure 3.1**, p. 53) was previously reported as unsettling for some drivers (Perrier et al., 2019). The 2nd symbol, designed after that of Mercedes-Benz, provided the most accurate responses and was the least confused with other systems during the matching task. Therefore, it seems important to symbolise the concept of headway distance on the symbol of this system.

Regarding LCC, the 3rd and 4th symbols, both omitting drivers' hands, received the most accurate interpretations. However, the definition used to decide whether drivers' descriptions of LCC was accurate did not take in account the limited capabilities and consequent requirements of certain systems asking drivers to keep their hands on the steering wheel during operation. When symbols included hands, they were less often interpreted as an LCC and more as an LDP, LDW, take-over request or a driver intervention feedback. Thus, it is important for designers to know that from a driver's perspective, hands being depicted or not on an LKA symbol is a meaningful detail that should be used to promote the appropriate use of the system. If a system is to be used hands-on this should be reflected by the symbol. In recent years, several incidents resulted from the misuse of an SAE level 2 system, with drivers being disengaged from the driving task and failing to regain control of their vehicle when required. We can summon the examples of an Uber system killing a pedestrian on March 18th of 2018 (NTSB, 2018) or that of a Tesla Autopilot crashing into a North Carolina police car on August 26th of 2020. A misinformative and permissive system coupled with an overly trustful and complacent driver can lead to building inaccurate mental models and consequent misuse of the system (Nielsen, 2010; Parasuraman & Riley, 1997). Misinformative because the symbol did not contribute to informing drivers of their duty to keep their hands on the wheel, and permissive because drivers are hardly constrained by the system to abide by their duty of staying alert and ready to take over. An appropriate LCC symbol might be a small step in promoting appropriate driver behaviour, but if hands are supposed to stay on the steering wheel, this should be made clear by the symbol. We could even envision dynamic symbols whose appearance would change depending on the situation and requirements of the system.

2. Are these symbols confused with other ADAS symbols?

As mentioned previously, the Mercedes-Benz-inspired ACC symbol was the least confused during the matching test, that is, the least associated with other systems (almost 100% of accuracy), whereas the ISO symbol was the most associated with a conventional CC system. Although we cannot conclude that there was a significant confusion for any of the ACC symbols evaluated in this research, there was a notable confusion between both types of LKA systems (i.e., LDP and LCC). Not only were LCC symbols sometimes interpreted as an LDP during the recognition task but also these two systems and their symbols were mutually confused about 30-60% of the time during the matching test. This means that there could be confusion not only when these symbols are used simultaneously on the same interface but also that there could be misinterpretation when they are present individually in a vehicle. Here again, the depiction of hands on the symbol did have an influence on confusion, resulting in the symbols being more confused with an LDP system. Yet, this confusion may not originate from the symbol used for LCC but rather from the LKA symbol used for LDP.

3. Are there flaws with the current ADAS symbols?

As concluded in Perrier et al. (2019), affordances seemed rather important for drivers when designing their own symbols and again when choosing which symbols best represented the system they were designing for. In a nutshell, affordances are the perceptions of the actions available to an individual in the environment due to their characteristics (Gibson, 2014; Norman, 1999), which can be extended by using tools (e.g., a car). Those actions can be approach behaviours as much as they can be avoidance behaviours, such as keeping a safe distance from a lead vehicle or from lane boundaries (Gibson & Crooks, 1938).

This can explain why the second ACC symbol was more successful by representing the headway, why hands on an LCC symbol are meaningful, and why the LKA standard symbol is not entirely appropriate for representing an LDP system. LDP is referred to as a 'single-bandwidth algorithm' for lane-keeping by Roozendaal et al. (2021), and is also described as a 'ricochet' or 'ping-pong' system by certain users or researchers (e.g., Burns, 2020). One could think that this is not what is suggested by the LKA symbol (**Figure 3.3**, p. 55): both lane markings are represented, which conveys the idea that the system operates on a lane-basis rather than a single lane-boundary basis, and there is no clear indication that departure or swerving from one's driving lane is key in its operation.

Figure 3.10 is an attempt to illustrate how a variant symbol for LDP could result from this affordance-principle, and also shows that new ideas may emerge despite the complexity to represent two systems that are closely related. Establishing LDP and LCC as two different standards should be considered as is now the case for ACC (ISO 15622) and cooperative ACC (CACC; ISO 20035). The international society of automotive engineering (SAE) for instance was making the distinction between LDP systems and LCC systems back in 2016 (SAE J3048).

Figure 3.10 Author variant pair of symbols for LDP and LCC. Illustrative purpose only.

To summarise, it appears that the headway distance between a driver's and a preceding vehicle is poorly represented on the standard ACC symbol despite its importance for drivers, while considering the danger of the confusion that exists between LDP and LCC systems on the market allowed to demonstrate how incompatible the LKA/LDP symbol is when used alongside an LCC symbol.

V. Conclusions

1. Standardisation of symbols design

The process of standardisation can be engaged by anyone who identifies the need for a standard in a field (e.g., an automaker). However, while the development of standards for interactive systems demands a human-centred design[††] approach (ISO 9241-210), the ISO/IEC Guide 74 for the consideration of consumers' needs as well as other standards for the production of graphical symbol variants (IEC 80416-1, ISO 80416-2, ISO 80416-3, and ISO 80416-4) and their evaluation (ISO 9186-1) do not refer to this design approach. It is unclear how the ACC or LKA symbols were designed, but this research shows that a systematic user-centred design (UCD) process should be followed to ensure that the symbols be understood and accepted by the users of those systems.

The UCD approach moves designers towards understanding and focusing on the future users' needs. The participatory design approach asks designers to go beyond that and treat users as active co-creators rather than just informers (Dell'Era & Landoni, 2014). This approach has been used successfully for the production and evaluation of software (Waller et al., 2006), interfaces (Pollard & Blyth, 1999) and symbols (Bhutkar et al., 2011; Sloan & Eshelman, 1981). But the extent to which users can be involved in such a creative process may vary depending on task complexity and users' skills (Marti & Bannon, 2009). While our research alone cannot be used to prescribe applying the UCD and participatory approaches to producing symbol variants for ISO standards, it does bring arguments in favour of these methods. Having users participate individually and collectively in the production but also in the evaluation of variant symbols allowed to point towards certain weaknesses of the ACC and LKA standard symbols.

2. Limitations and future research

In the present research, drivers partook during an online survey, which presents certain limitations and disadvantages compared to face-to-face

[††] Broader term than user-centred design but used equivalently by the ISO.

research methods. Firstly, there is an inherent sampling bias when using web-based research tools, in that that respondents are most likely comfortable enough with technologies to respond to online surveys, thus ignoring an unknown percentage of the population. Secondly, there may be an individual bias towards responding to surveys, which could have been accentuated by this survey not being compensated monetarily. Thirdly, the level of engagement of respondents in the task cannot be controlled. Finally, some responses might have been the result of two or more respondents.

In our previous research, drivers were only asked to acknowledge the existence of LDP systems but not design a symbol for this system. This probably imposed fewer constraints on their designs for the LCC symbol to try and make it look different from that of an LDP symbol. Therefore, additional focus group sessions should be conducted with drivers to produce symbols both for the LDP and LCC systems.

In our next research, we will consider the usability of ACC symbols being used for indicating the different parameters of the ACC system, namely the driver pre-set gap distance and system mode. Indeed, the symbol designed by Mercedes-Benz, which was the most recognised in this study, is not only used to indicate system status but also to set and indicate the preferred headway distance and the detection of a lead vehicle, thus, indicate whether the user’s vehicle will drive at the driver pre-set speed or adapt to the traffic speed. Displaying this information on such limited space when other alternatives exist may be a counterproductive choice that could hinder drivers’ attention to the driving task.

In future research, we may consider vehicles equipped with both LKA systems and the potential influence of symbols on their usability. Our previous (Perrier et al., 2019) and current research suggest that the design of LKA symbols could modulate the perceived level of assistance provided by the associated LKA system. With the increasingly complex arrangements of controls inside our vehicles and the different implementations of LKA systems, it is unclear whether drivers will face new challenges and how symbols or other elements of the DVI could help tackle these.

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Appendices

Appendix 3.1 Survey questions and answers

Order	Question	Responses
1	(...) country in which you are currently living:	○ [list of countries]
3	(...) [this country] has been your main residency for the past five years?	• Yes • No
2	(...) country in which you have spent the most of your life:	○ [list of countries]
5	(...) your gender:	• Male • Female • Prefer not to say
6	(...) your age:	○ [slider]
7	(...) highest grade or level of school you have ever completed?	• Primary education only or less • Secondary education or less • Bachelor's, Associate's degree, A-level, GNVQ, BTEC or equivalent • Master's degree or equivalent • Doctorate degree or more
8	(...) background in any of the following fields?	• Design: Graphic, UI, or Visual • Design: Industrial or Mechanical • Design: Other fields • Human Factors: Automotive • Human Factors: Other fields • Professional Driver: Car or Truck
4	(...) currently hold a valid driving license?	• No, I don't have a driving license • Yes, but I can't drive in [current country] • Yes
9	When did you obtain your driving license?	○ [slider]
10	During this last year, how frequently have you been driving a car or a truck?	• I haven't been driving • Less than once per month • More than once per month • 1-3 days per week • 4-7 days per week
11	What do you know about driving assistance systems?	• I don't know what it is • I've only heard of it • I've seen demonstrative videos • I've seen someone using them • I've already used them • My work is related to them

Appendix 3.2 ADAS and their definitions used for interpretations of the responses. † Indicates the systems made-up to capture the nuances in the respondents' responses.

System		Description
Intelligent Speed Assistant	ISA	Warns drivers of speeding and/or actively provide support to prevent speeding.
Forward Collision Warning	FCW	Warns the driver when it detects an impending collision.
Forward Automatic Emergency Braking	FAEB	Warns the driver and/or brakes when it detects an impending collision.
Automatic Emergency Steering	AES	Automatically steers a vehicle to avoid an impending collision.
Speed Limiter	SL	Prevents drivers from going above a set-speed.
Cruise Control	CC	Maintains the vehicle at drivers' set speed.
Distance Warning	DW†	Warns the driver of insufficient gaps from a vehicle in front.
Distance Assist	DA†	Intermittently assists the driver to keep a safe distance by decelerating or braking the vehicle.
Distance Control	DC†	Automatically maintains a safe distance from the vehicle in front.
Adaptive Cruise Warning	ACW†	Warns the driver of speeding and of insufficient gaps from the vehicles in front.
Adaptive Cruise Assistant	ACA†	Intermittently assists the driver to not speed or to keep a safe distance by decelerating or braking the vehicle.
Automatic Car Following	ACF†	Automatically maintains speed to match a lead vehicle's speed and keep a safe distance.
Dynamic Cruise Control	DCC	Automatically maintains a preferred set-speed and apply brakes when steering is applied.
Adaptive Cruise Control	ACC	Automatically maintains a preferred set-speed and set-gap from the vehicle in front to keep a safe distance.
Lane Departure Warning	LDW	Warns the driver when the vehicle is about to or crosses lane markers.
Lane Departure Prevention	LDP	Automatically and intermittently steers a vehicle to avoid encroaching lane markings and straying from the current lane of travel.
Lane Centring Assist	LCA	Automatically and intermittently assists to stay in the centre of its current lane of travel.
Lane Centring Control	LCC	Automatically and continuously steers a vehicle to maintain it in its current lane of travel.

Chapter IV

Usability Testing of Three Visual HMIs for Assisted Driving: How Design Impacts Driver Distraction and Mental Models

Abstract

There is a variety of visual human-machine interfaces (HMI) designed across vehicle manufacturers that support drivers while supervising driving automation features, such as adaptive cruise control (ACC). These various designs communicate the same limited amount of information to drivers about their ACC system and it is unclear which HMI designs impact driver distraction the least or how their design could be modified to help drivers develop more accurate mental models of their ACC system. Using a user-centred design (UCD) approach, we designed a speedometer to inform drivers about some of the system's capabilities and then invited 23 drivers to use ACC in a low-fidelity driving simulator to compare the usability of three HMIs using eye-tracking, response times, and qualitative data. Our attempt at designing an intuitive and more informative speedometer received mixed results, but design recommendations are given regarding the indication of the set target speed, set time gap between vehicles (headway distance), and system mode (conventional or adaptive cruise).

I. Introduction

As advanced driving assistance systems (ADAS) increasingly take over the basic operational aspects of driving, drivers are pivoting to a hybrid role of supervisor and active controller for which all informational needs are not yet fully understood (see Sarter & Woods, 1995). Instead of entirely manoeuvring the vehicle themselves, drivers must now ensure that the activated systems operate safely and within their technical boundaries, or operational design domains. Doing so requires at least an understanding of how each system functions and the ability to gather information about a system's status at any given time. Consequently, there is a need to consider how human-machine interfaces[‡‡] (HMI) should be designed in terms of the type of information necessary for supervision and decision-making, and what information might be redundant (e.g., Beggiato et al., 2015). The form in which this information is presented is of particular importance for the users of adaptive cruise control[§§] (ACC), or SAE Level 1 (L1) assisted driving (SAE International, 2018), as they find themselves in a position where they need to simultaneously supervise and steer their vehicle. Any interaction with the HMI then becomes a potential distraction to their primary driving task if conducted for too long (Harvey et al., 2011), while remaining an essential part of their supervisory role. It is therefore important for drivers to develop accurate mental models of their driving-assisted vehicles to minimise driver distraction, but also for designers to develop HMIs with good usability that help reduce driver distraction and provide appropriate support to drivers in their dual roles. In this paper, we explore the importance of visual HMIs and usability, and how the latter relates to the concepts of driver distraction and mental models. We then report data from a driving simulator study and semi-directed interviews to try and address the issues further developed in the following sections.

1. Usability for driver supervision

What is usability?

Usability defines the degree to which a product eases the use of its functionality (Nielsen, 1994). The international organisation for standardisation (ISO) decomposes usability into three subcomponents: effectiveness, efficiency, and satisfaction (ISO, 2010). Respectively, these components refer to how good the outcome of using a product is, how much time and effort is required, and how satisfying it is to use. Usability can be expanded to consider other product attributes such as the aesthetics, emotions, and engagement of the users, as well as individual and social factors (Bevan, 2009). Altogether these factors form

[‡‡] Interface: any physical means of translating and transmitting a signal intelligible by one party into a signal intelligible by another party, in either direction.

[§§] Adaptive cruise control (ACC) accelerates the vehicle up to a chosen target speed and decelerates to slower lead vehicles to maintain a set headway time.

the user experience (or UX), which relates to the users' perceptions and can be seen as more focused on the satisfaction of using a product than usability is alone. Although secondary to safety, the satisfaction of using a product may matter very much in some cases. In the case of automated vehicles, these systems have the potential to improve road safety (Kalra & Groves, 2017). It is therefore essential to propose products that are both very usable and very engaging for drivers when the goal is to have drivers use these technologies (Nordhoff et al., 2019).

How does usability relate to driver supervision?

Driving with an assisting or automated system requires redefining the driver's role. In the case of ACC, drivers retain lateral control but rely on ACC to direct the vehicle's longitudinal control. Because of system boundaries that the vehicle alone cannot always detect, a supervisory role is passed on to the driver upon activation of ACC. For instance, the sensors may fail to detect a vehicle ahead or not be equipped to detect curves and decelerate in response. Consequently, in this supervisory control paradigm (Sheridan & Parasuraman, 2005) the driver is required to plan the use of the system, command the system, monitor it to maintain mode awareness, intervene if necessary, and possibly learn from the interaction to update their mental model (i.e., the internal representation of how a driver believes a system works and what they believe the system can or cannot do; Norman, 1983).

Accurate mental models are a prerequisite at every stage of the supervisory control paradigm, but notably whilst monitoring a system for drivers to appropriately distribute their attention towards and between the different driving tasks. Maintaining mode awareness about a system is fundamental to avoid mode confusionClick or tap here to enter text. or automation surprise (Carsten & Martens, 2019; Sarter et al., 1997). Nonetheless, monitoring a system via the HMI should not prevent maintaining situation awareness of the external environment and it should be one role of the HMI to convey relevant information about an ADAS in a pleasant but efficient manner. Therefore, it is essential that HMIs have good usability to avoid driver distraction, facilitate the maintenance of situation awareness, and guide the formation of appropriate mental models.

2. Driver distraction: What, why, and how

What is driver distraction?

We will hereby define driver distraction as the misallocation of a driver's attention towards activities preventing the adequate maintenance of situation awareness and vehicle control (but see Regan & Hallett, 2011). This adequacy is therefore determined by the current automation level of the vehicle, where maintaining situation awareness for users of L3 is not as fundamental as it is for users of L1, for instance. Furthermore, distraction can occur on several channels, including visual, auditory, tactile, cognitive, and/or physical (Regan & Hallett, 2011; Young & Regan, 2007). Therefore, forcing drivers to interact with the HMI for too long while using ACC should be avoided given their responsibilities as supervisors and active controllers.

Why is visual distraction important to consider?

Driving is predominantly a visual-spatial-manual task (Sivak, 1996; Young & Regan, 2007), and according to a review by Lee (2008, p. 525), road collisions usually happen because one or more parties "fail to look at the right thing at the right time". This failure to attend important information within the environment could be due simply to inattention—like a driver misprioritising their attention—or to distraction, that is, inattention due to a concurrent activity and/or a failure to self-regulate their attention (Regan et al., 2011). Having a visual HMI that supports drivers in their supervisory role is therefore crucial and regulating the sources of visual distraction in our vehicles an important challenge to tackle for as long as drivers are involved in the driving task. One advantage of visual HMIs over other sensorial channels is the opportunity to communicate information about a system's status, availability, and capabilities, at any given time and at a low attentional cost—the same information would not be constantly available via the auditory channel and would be much less efficient to gather for instance.

How to measure driver distraction?

Distraction, be it cognitive or visual, can be estimated in numerous ways. Some of these metrics—such as a task's completion time, user accuracy, human effort (ISO 9241-11:2018), eye fixation duration, total glance time, or the number of glances (ISO 15007-01)—can also be used to evaluate a system's efficiency. Consequently, the visual efficiency of an HMI used during a monitoring task can directly reflect the level of visual attention allocated at the expense of other driving tasks. Moreover, it is usually considered that, during manual driving, any glance away from the road lasting more than two seconds should be prevented (Klauer et al., 2010) and that the cumulative time spent gazing away from the road should never exceed 12 seconds (see ISO 15007-01; NHTSA, 2013) as these numbers have been associated with higher risks of crashes. Finally, it is also common practice to estimate a driver's cognitive distraction using subjective assessments of situation awareness or mental workload as a complement to other driver distraction metrics (Abbasi & Li, 2021).

3. Mitigating driver distraction

Preventing driver distraction altogether is unachievable and the most reasonable manner to mitigate it is to reduce its occurrence and duration. Regulations, standards, and guidelines are methods of promoting good design practice across vehicles and ensuring consistency of their many aspects. For example, the way ACC should function and how its symbol should look (ISO 15622), the way symbols should be researched and designed (FHWA-RD-03-065; IEC 80416-1), where to place interface elements considering the driver's eyes position (SAE J941 2010-03), when to display some of the parameters of ACC on the HMI, such as the set speed, set time gap, and detection of lead vehicles (SAE J2399 2021-10), or again, how to evaluate the distraction engendered by visual-manual secondary tasks (NHTSA, 2013). But while there are many documents with the potential to help improve our vehicles' usability, they are often overlapping and sparsely dedicated to the visual design of HMI elements used in our driving-assisted vehicles, leaving designers in the unknow of how to design their ACC-related elements to convey information most efficiently.

Amid the user-related research conducted on ACC, few studies have investigated how to mitigate driver distraction or how to develop appropriate mental models for this system via the HMI. François et al.

(2017, 2019), for instance, compared the efficiency and usability of different speedometer designs and truck HMIs in the context of CC to inform design choices that would help reduce driver distraction using eye-tracking data, task completion times, and questionnaires—although, not in the context of ACC. Other studies were conducted where authors evaluated the help that would bring an HMI showing the technical limitations of an ACC system (Saffarian et al., 2013; Seppelt & Lee, 2007), but only one concerned the development of mental models (Seppelt & Lee, 2019). Moreover, these studies had little repercussion on the development of HMIs for market vehicles. Finally, a research team compared how many eye fixations and how much time was needed by drivers to say whether ACC was activated or not based on the symbol (Monsaingeon et al., 2021). They did not find a significant difference. However, the design of the symbols giving this information was the same between the vehicles that they used; the only difference for this task was the HMI layout. Consequently, there are still opportunities for the HMI designs of L1 vehicles to be researched and improved, and for the variety of HMIs on the market to be made more consistent.

4. The ACC systems, their HMIs, their issues

Since the regulations, standards, and guidelines on ACC systems are not exhaustive or constraining regarding some of their technical aspects, all systems are not equal: some cars can decelerate down to a full stop while some will require the driver to take over if going below 20 mph (30 km/h), depending on whether a stop-and-go function is available or not. In the first case, the system is called 'full speed range,' while in the second, it is termed 'limited speed range' (see ISO 15622:2018). In parallel, different cars allow drivers to choose from different ranges of speed to set: one car may allow setting a target speed for ACC between 15 mph and 95 mph, while another car could propose a range starting from 20 mph and up to 90 mph. The issue is that, except for the maximum target speed, none of this is indicated via the HMI and drivers must have done their research beforehand or try and fail to become aware of these system boundaries. 'Signifiers' can refer to "perceivable indicators that communicate appropriate behaviours to a person" in the affordance framework (Norman, 2013). Therefore, this signifier issue could be a hindrance to the development of mental models, and consequently to road safety if this were to lead to mode confusion when drivers use a new system that looks the same but behaves differently.

Equally, because of the lack of studies comparing existing HMI designs and, consequently, the lack of relevant information in the guidance available to designers, all visual HMIs are not equal: indicating the ACC system's target speed can be achieved differently, as well as showing the time gap (or headway distance) to maintain, or again the way of indicating the detection of a lead vehicle. These pieces of information are usually indicated via three graphical elements on the HMI (**Figure 4.1**): a strip and/or an arrowhead on the speedometer, a graphical view of the driving scene, and/or the graphical symbol of the system. Some HMIs will only use an arrowhead, while others will also use a strip, or only indicate the target speed in written, or use a combination of all three options. To set the headway distance, some HMIs will use a side-view of the scene (**Figure 4.1**) while others will show a bird's-eye view of the scene or even use the graphical symbol, which could make it more demanding for drivers in the latter case given the smaller size of symbols compared to scene views (e.g., Lindberg & Näsänen, 2003; McDougall et al., 2000; Schuetz et al., 2019; Vertegaal, 2008). Finally, indicating the absence of a lead vehicle is sometimes indicated by greying the car of the ACC symbol and sometimes by only showing an outline version, which can unpredictably impact the recognition time of the symbol (Arledge, 2014). Sometimes, this information is instead indicated via a bird's-eye view of the driving scene by removing the lead vehicle model. Some of these designs could present efficiency issues and therefore exacerbate driver distraction.

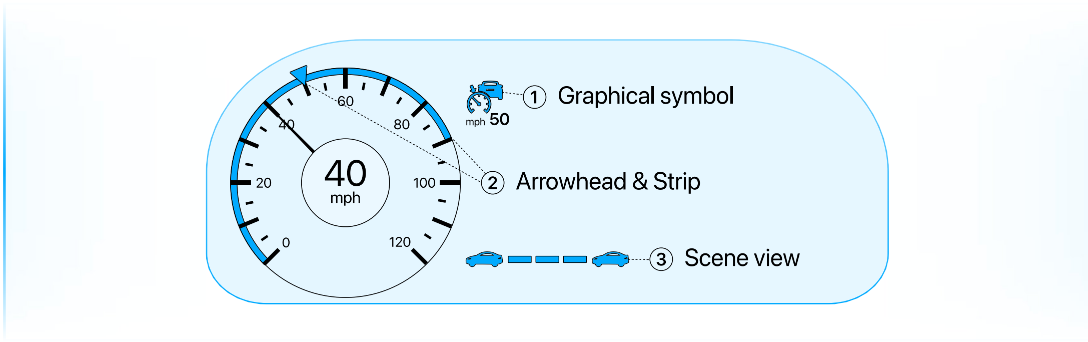

Figure 4.1 Mock HMI showing three common elements supporting the use of ACC: 1) graphical symbol; 2) arrowhead and strip; 3) scene view.

5. Solving the design issues

These design issues have not been openly researched despite their potential impact on driver safety and the importance of informing designers about how to conceptualise visual HMIs that support the development of mental models and minimise driver distraction. To examine the efficiency issues mentioned in the previous section, we regrouped different designs available on the market into three HMIs to compare them: *simple*, *advanced*, and *custom*. The *simple* design mimicked the most minimalistic HMIs and displayed the information in an integrated manner. The *advanced* design had more visually complex elements than the simple HMI and was more spaced. Lastly, the *custom* design was approached with both philosophies in mind and integrated a custom speedometer designed to improve the signifier issue mentioned earlier. We were interested in which designs were the most efficient to communicate the same information to users of ACC, and whether our custom speedometer helped drivers to develop a more accurate mental model of their ACC system. To summarise, the research questions addressed were:

- Does HMI design affect drivers' efficiency to conduct routine tasks with an ACC system?
- Does our custom design communicate the capabilities of the ACC system efficiently?

II. Material and Methods

1. Experimental design

A. Participants & design

After approval from the University of Leeds Research Ethics Committee, 24 participants with a valid driving license issued no less than 3 years prior to the study were recruited via a mailing list. All regularly drove in the UK, had normal vision and hearing, and received £20 as monetary compensation for their participation. One participant who had strabismus (crossed eyes) could not be calibrated to the eye-tracker and was therefore not asked to complete the procedure. Three other participants had to be removed from the eye-tracking data analyses due to technical issues with the eye-tracker: misdetection of the markers, miscalibration over time, or repeated failure to detect the participant's eyes because of their eyeliner. The final sample was composed of 20 participants (9 females and 11 males) between the ages of 20 and 64 years ($\bar{x}$ = 42.65, s = 12.7) for the eye-tracking data, 23 participants (10 females and 13 males) for the questionnaires, and 22 participants (10 females and 12 males) for the semi-directed interviews (see p. 106). The experiment had a mixed factorial design with repeated measures with the fixed effects being the HMI (*simple* | *advanced* | *custom*) as a within-subject factor and the System Range (*limited range* | *full range*) as a between-subject factor. The order of the conditions was counterbalanced across participant.

B. Driver-vehicle interfaces

The design differences that we addressed earlier (p. 96) and used for the design of the three HMIs are summarised in **Table 4.1**. The next sub-sections provide more details for each element and reference the original equipment manufacturers' (OEM) designs for comparative and illustrative purposes.

Table 4.1 Design differences for each ACC parameter between all three HMIs.

Simple	Advanced	Custom
		
		
Adaptive mode shown by blue car symbol. Conventional mode shown by hollow car.	Adaptive mode shown by blue car symbol. Conventional mode shown by grey car.	Adaptive mode shown by blue car symbol. Conventional mode shown by absent vehicle on scene view.
		
Distance set by increasing the number of stripes below the car, from top to bottom.	Distance set by increasing the number of stripes between the cars, from left to right.	Distance set by increasing the number of stripes between the cars, from the bottom up.
		
Set target speed indicated by a single blue arrowhead and written below the graphical symbol.	Target speed indicated by blue arrowhead and written below the graphical symbol. System speed range shown by blue strip.	Left: green arrowhead shows set speed; blue strips show system range. Right: when the driver sets the speed, the green strips show driver range.

a. Symbols & assistance graphics

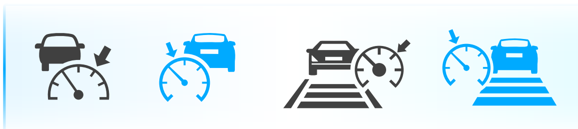

Figure 4.2 Left: standard ISO symbol (dark) and reworked version (blue) used for this study. Right: original Mercedes-Benz symbol (dark) and reworked version (blue) used for this study.

The two symbols selected for this study received the highest recognisability rates in Perrier et al. (2021) but were not previously tested for usability *in situ*. The ISO-based symbol (**Figure 4.2**) was 10 × 8 mm, with the car being 6 × 4 mm. The Mercedes-based symbol (**Figure 4.2**) was 13 × 8 mm with each headway band being 5-9 × ~1 mm. The headway bands on the side-view graphic (**Figure 4.3.c**) were 7 × 2 mm, while those of the bird's-eye view graphic (**Figure 4.3d**) ranged from 9 × 3 mm to 13 × 6 mm.

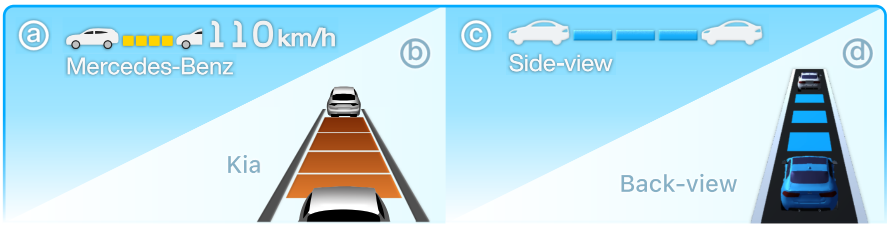

Figure 4.3 Assistance graphics showing the headway distance of an ACC system. (a) Mercedes-Benz side-view graphic showing both headway distance and target speed; (b) Kia bird's-eye view graphic; (c) side-view and (d) bird's-eye view graphics produced for this study for the advanced and custom HMIs, respectively. Graphics are reproduced and not to scale.

b. Speedometers

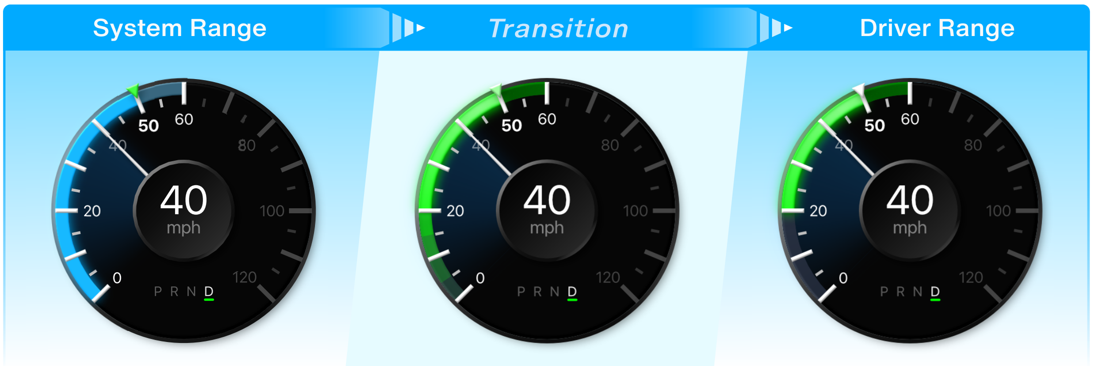

Figure 4.4 The custom speedometer momentarily changes appearance when the target speed is set to reveal the range of speed available to drivers.

The *simple* and *advanced* HMIs (see **Table 4.1**) always displayed the target speed below the ACC symbol. The *advanced* HMI had a blue arrowhead marker and a blue gauge running along the speedometer from the minimum system speed (i.e., 0 or 20 mph depending on the system speed range condition) to 90 mph. The *custom* HMI had a green arrowhead marker to increase the contrast with the blue strip, and a custom strip running from the minimum system speed to the posted speed limit to declutter the speedometer. Finally, during drivers' interaction with the target speed, the strip turned green and ran from the minimum driver speed (i.e., 20 mph) rather than the minimum system speed (i.e., 0 or 20 mph) to communicate the difference between system range and driver range (**Figure 4.4**). This colour change also gave more feedback to attract attention to this element (Carrasco, 2011; Kim et al., 2011).

C. *Apparatus*

The research employed the University of Leeds fixed-base low-fidelity driving simulator operated on a Stone PC running Windows 10, using custom-made software, Intel Core i7 CPU (3.40 GHz) and 32 GB of RAM. The visual simulation was displayed on a Samsung 40” wide-screen 1920×1080 (16:9) LCD monitor, rendered at 60 Hz. An IPS QHD 10” 2560×1600 (16:10) LED monitor was used for providing the instrument panel and placed behind the steering wheel. Vehicle control inputs were recorded via Logitech G27 dual-motor force feedback steering wheel and pedals (**Figure 4.5**).

Figure 4.5 Setup of the University of Leeds fixed-base low-fidelity driving simulator and controls assigned to the buttons of the steering wheel.

A head-mounted Pupil Core eye-tracker by Pupil Labs was used to record participants’ eye gazes at 60 Hz. Calibration was achieved using a single marker displayed at the centre of the 10” monitor and having participants move their heads in both horizontal and vertical axes and then circularly while maintaining their gaze on the marker.

D. *Tasks*

Participants performed three routine driving tasks encountered when using an SAE level 1 ACC system. The first driving task was split into two subtasks (1a and 1b), for a total of 4 discrete tasks: (1a) decreasing the system’s target speed from the posted speed limit to a value below that speed limit; (1b) increasing the target speed to the posted speed limit; (2)

increasing or decreasing the minimum headway distance; and (3) identifying the system's mode/state, that is, whether the system was operating as a conventional CC or as an adaptive CC. Tasks 1a, 1b, and 2 were conducted manually by pressing the controls on the steering wheel. Task 3 was answered verbally by indicating 'yes' or 'no' to whether a lead vehicle was detected. Moreover, during this task only, the Mercedes-based symbol of the *simple* HMI was replaced by the ISO-based symbol to make the size of the symbol equal to the one used for the *advanced* HMI.

E. Procedure

Before the experiment, participants were emailed information about the experiment and safety procedures regarding the pandemic. The experimenter welcomed them to the simulator facility and took them to the experiment room. They were first asked to fill out a consent form, demographics, and experience questionnaires on an iPad.

The participants were then introduced to the driving simulator and were familiarised with the driving controls during a practice drive. During this drive, the experimenter first trained the participant on the four tasks that they needed to conduct by giving them verbal instructions. The experimenter then pressed a key on the keyboard to activate the automated delivery of the pre-recorded verbal instructions for drivers to practice the tasks autonomously, just like they would during the experimental procedure. Each of the four tasks was presented at least once with each HMI. Once they felt comfortable enough to proceed with the experiment, the eye-tracker was installed and calibrated, and the first of the three experimental drives began. Both drives lasted approximately 20 minutes and participants were proposed to have a short break if they needed. The order in which each participant would use the three HMIs and whether they would use the limited- or full-range system was counterbalanced. The order of the tasks was counterbalanced with the speed decrement task 1a always appearing before the speed increment task 1b. The values to be set by participants were also counterbalanced.

The observation of ACC usage began on a UK rural road with a speed limit posted at 60 mph and behind another car. Each participant started by driving manually and was asked to activate ACC as soon as they noticed the grey ACC symbol on the HMI—this symbol appeared once the speed was above 20 mph. The participant then drove through a village with a speed limit of 40 mph, and finally drove through a motorway section with a speed limit of 70 mph. Participants were instructed to adjust their target speed to the posted speed limit when they detected a speed limit sign or when a visual-auditory notification appeared on the interface—the speed limit was always displayed on the HMI. Each task prompt appeared at equally spaced points on the road and was communicated auditorily via the smaller screen speakers. The HMI would disappear for as long as the instructions were heard to prevent participants from responding before receiving all the instructions. After the HMI reappeared, participants had 10 seconds to respond to the task, after which the data collection would stop for this trial. In case they failed to respond correctly, they received the instructions again but the trial was excluded from data analyses. All four tasks appeared four times on each road section in a predetermined order. The target speed was incremented or decremented by 5 mph and could not be asked to be set at more than 20 mph below the speed limit. The headway distance was restricted to between one and three bars.

2. Measures

A. Behavioural & verbal

Unity® Game Engine was used to implement the HMIs and record task-related behavioural measures. For each trial, the system timestamps for drivers' first and last manual inputs were recorded to compute their response times (RT), the accuracy of their response, and whether any mistake occurred, such as pressing the wrong button or exceeding the target value. Participants' verbal responses were noted by the experimenter, as were the trials where participants were distracted or not ready for the task (e.g., talking to the experimenter or trying to get back the control of their vehicle after veering off the road).

Because of a bug encountered in Microsoft Excel, the timestamps of 12 participants were overwritten by the scientific notation after opening and closing the original CSV files. These timestamps were then re-estimated using the timestamps registered by the eye-tracker and participants' RT computed in real-time by the HMI during the experiment (see the next section for details).

B. *Eye-tracking data*

For each frame, Pupil Labs' software recorded the system timestamps, gaze coordinates, and whether eye gazes were estimated to be inside the frame of the HMI. This last measure was defined using six markers appearing for 10 seconds around the edges of the screen at the beginning of each trial and after the instructions had been heard.

To analyse the visual demand (i.e., the efficiency) required by each task we computed the total glance time (TGT) spent looking at the HMI before a correct response was recorded. The available time window was between the HMI onset time and the six markers' offset time, that is, a time window of 10 seconds. For tasks 1a, 1b, and 2, we also accounted for the fact that drivers' last input could have occurred between two glances. Therefore, we included the glances that occurred 1300 ms after the last input, as 90% of the peri-response glance intervals (i.e., the intervals between the glances occurring during a participant's response) occurred before 1306 ms, and the average post-response glance interval was 1646 ms. To avoid confusion with the normal definition of total glance time (TGT; ISO 15007-1) we will refer to this metric as 'extended total glance time' (xTGT). Moreover, the trials in which the duration of the xTGT was inferior to 120 ms multiplied by the number of glances were discarded as it is physically impossible to have glances shorter than that (see ISO 15007-1:2014).

C. *Questionnaires*

After each drive, participants completed the rating scale of mental effort (RSME; Zijlstra, 1993), the NASA raw task load index (R-TLX; Hart & Staveland, 1988), and the system usability scale (SUS; Brooke, 1986) questionnaires.

The RSME was used to assess subjective workload as it has the advantage of being sensitive (Sauro & Dumas, 2009) while being easy to administer since it consists only of a vertical line that participants needed to cross with a pen on the tablet to automatise the computation of the score.

The R-TLX was also used to assess subjective workload as it discomposes the variable into 10 items and therefore is more complex than the RSME while remaining easy and quick to administer.

Finally, the SUS was chosen for its short length and wide range of applications with minor adaptation (see Sauro, 2015).

D. Semi-directed interviews

After the three drives, participants were interviewed. These post-experimental semi-structured interviews aimed to gather qualitative feedback on the interfaces. Participants were asked to indicate which interface they thought was the most pleasant to use, the easiest to understand and use for the first time (intuitiveness), the easiest to use after not using it for an undefined period of time, the most confusing, the one most preventing errors, and the one allowing the most accurate, correct, and quick responses. Participants were asked to elaborate on each response. Then, they were asked whether they understood the design of the *custom* speedometer, and finally were asked to choose which version of the different elements of the interfaces they would prefer (i.e., speedometer, written target speed, symbol, and headway). The speedometer and written target speed were considered at first as one ‘speed’ element but were then separated into two distinctive items after six interviews based on participants' answers. Consequently, the following 15 participants were asked to choose between having a written speed, a marker on the speedometer, or both. One participant had to leave before the interview, which resulted in only 22 participants being considered for this part of the analysis.

3. Data analysis

A. Behavioural data

a. Extended Total Glance Time (xTGT)

We conducted mixed-effects median regressions for the *speed decrement task 1a*, *speed increment task 1b*, and *headway task 2* using the *lqmm* package (Geraci, 2014) in R (R Core Team, 2020). This type of regression does not assume a particular data distribution, is robust to outliers, and allows comparisons between groups of data at their medians rather than their means. For the *system mode task 3*, we conducted a mixed-effects gamma regression—a regression assuming that the data follows a gamma distribution—using the *lme4* package (Bates et al., 2015) on the TGT for the trials where there was no vehicle detected, which halved the data and consequently prevented the use of a mixed-effect median regression. All significance thresholds were at 95% ($\alpha = .05$).

For the speed tasks 1a and 1b we used two different statistical models: the first modelled the overall effect of the HMIs whereas the second modelled the effects of the strip size, which only concerned the *advanced* and *custom* HMIs. The first model was also used for tasks 2 and 3 (the headway setting and system mode reading).

As random effects, we modelled an intercept for each participant to keep our repeated measures data independent from each other (Judd et al., 2012).

As fixed effects for the 1st model, given our hypothesis that the custom HMI would be more efficient than the other two HMIs, we used an orthogonal simple coding to compare the *custom* level of the HMI variable to each of the other levels (*HMI* Ψ_1: *simple vs. custom*; *HMI* Ψ_2: *advanced vs. custom*). We also modelled the trial number as a covariate to account for any learning effect and the number of glances needed to respond as a covariate to explain an important part of the variance.

$$xTGT = HMI\ \Psi_1 + HMI\ \Psi_2 + Glances + Trial + (1 \mid Participant)$$

As fixed effects for the 2nd model, we used a dummy coding for the effect of the HMI, with the *custom* level as 0 and the *advanced* level as 1, a simple coding for the effect of the system range (*System Range* Ψ*: limited* *range ACC vs. full-range ACC*), a simple coding for the effect of the speed-limit restriction on the *custom* strip (*Driver Range* Ψ_1: 40 mph vs. 70 mph; *Driver Range* Ψ_2: 60 mph vs. 70 mph), the interaction term between the HMI and system range (*HMI* Ψ × *System Range* Ψ), the interaction terms between system range and driver range (*System Range* × *Driver Range* Ψ_1; *System Range* × *Driver Range* Ψ_2), and again the trial number and the number of glances as covariates.

$$
\begin{aligned}
xTGT = {} & HMI\ \Psi + System\ Range\ \Psi + Driver\ Range\ \Psi_1 + Driver\ Range\ \Psi_2 + \\
& HMI\ \Psi \times System\ Range\ \Psi + \\
& System\ Range\ \Psi \times Driver\ Range\ \Psi_1 + \\
& System\ Range\ \Psi \times Driver\ Range\ \Psi_2 + \\
& Glances + Trial + (1\,|\,Participant)
\end{aligned}
$$

Coding the *custom* level of the HMI variable allowed to model the system range and driver range variables on this level only and ignore the *advanced* level. The interaction between HMI and system range then would tell us if the shorter or longer lower part of the strip had different effects on the xTGT according to the HMI.

To clean our data and remove unusual values we only kept the trials ① where no error was committed, ② where the number of glances to respond did not exceed three as the trials with more than three glances represented less than 2% of the data and popped out as outliers when using visual methods, and finally, ③ where no more than one glance exceeded 2 seconds or where the only glance ported to the HMI did not exceed 2 seconds as this would be considered as a distraction to the primary driving task according to the NHTSA guidelines (NHTSA, 2014).

b. Response Times (RT)

The same procedure conducted for the xTGT was followed for the RT, with the exception that we did not model the number of glances needed to respond. Instead, we modelled as a covariate the difference between the task value and the current speed or headway value to account for higher values being associated with higher RTs—for instance, if ACC were set at 60 mph and the task asked drivers to set it to 55 mph, this would be modelled as −5. This variable will be referred to as ‘speed decrement’ for task 1a and ‘speed increment’ for task 1b. Finally, two extreme values were removed for the regression on the RT of the headway task but are still shown in **Figure 4.10**.

B. Questionnaires

For the questionnaires, all 23 participants that participated in the drives were considered.

a. Rating Scale of Mental Effort (RSME)

We conducted a mixed-effects gamma regression on the RSME scores—ranging from 0 to 150—with a simple coding to compare the *custom* level of the HMI variable to each of the other levels (*HMI* Ψ_1: *simple vs. custom*; *HMI* Ψ_2: *advanced vs. custom*), drivers' age centred on its mean as a covariate, the years of driving experience, and participants were entered as a random effect. The data not being normally distributed, a gamma distribution was chosen based on the QQ-plots of the regression models generated. The interactions were not modelled due to convergence issues.

b. Raw Task Load Index (R-TLX)

Responses to the TLX items were computed into an overall score ranging from 0 to 100. Because of the limited number of data points and the non-normality of their distribution, we conducted a Friedman test as a non-parametric equivalent to the analysis of variance.

c. System Usability Scale (SUS)

After considering a mixed-effect censored regression with a censored normal distribution (Hu, 2019) using the *lme4cens* package in R (Kuhn, 2021), diagnostics were not satisfactory and therefore, we conducted a Friedman test as a non-parametric equivalent to the analysis of variance. Responses to the SUS items were computed into an overall score ranging from 0 to 100, resulting in a bounded outcome score. The scores were not normally distributed as is usually observed in other research (see Lewis, 2018), our scores being skewed towards the upper boundary.

III. Results and Analyses

1. Efficiency

A. Setting the target speed

The overall distributions of drivers' xTGT and RT in the speed decrement task 1a are illustrated by HMI in **Figure 4.6** and **Figure 4.8**. All regression tables are available as Appendices **Appendix 4.1** to **Appendix 4.6**.

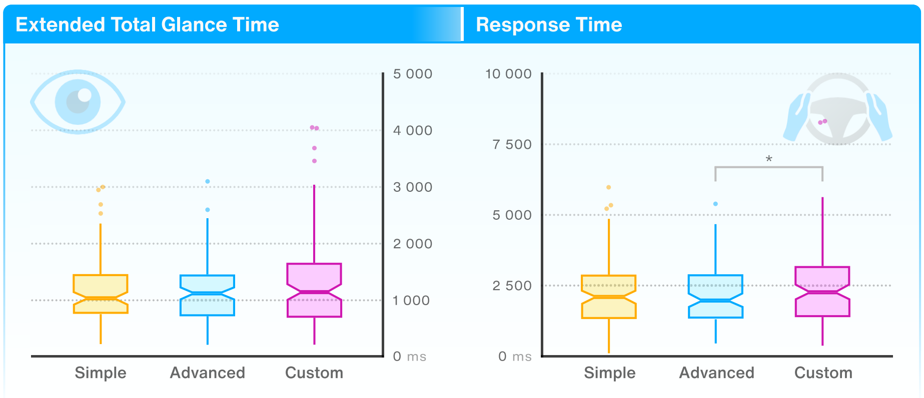

Figure 4.6 Boxplots with 95% CI (notch) of drivers' extended total glance times (xTGT; left) and response times (RT; right) for the speed task (1a) depending on the HMI and system speed range used. Outliers are shown.

From the first statistical model comparing all three HMIs, we found that drivers were slower (RT) to decrease their target speed while using the *custom* HMI than when using the *advanced* HMI (β = 269.06, 95% CI [7.15, 530.96], $p = .04$). In other words, the *custom* design degraded the efficiency of the HMI when drivers needed to set the target speed of their ACC system to a value below the posted speed limit. One explanation could be the absence of a written target speed on the HMI, like the *simple* and *advanced* HMIs had below the ACC symbol. Due to the imprecision of the eye-tracker, we cannot be certain of exactly when and if drivers opted for this strategy or not, as some had reported doing it and others not. Given that no difference was observed on the xTGTs, the disadvantage of the *custom* HMI may not have come from locating the current target speed on the speedometer, but from setting the target speed to the instructed value below the speed limit.

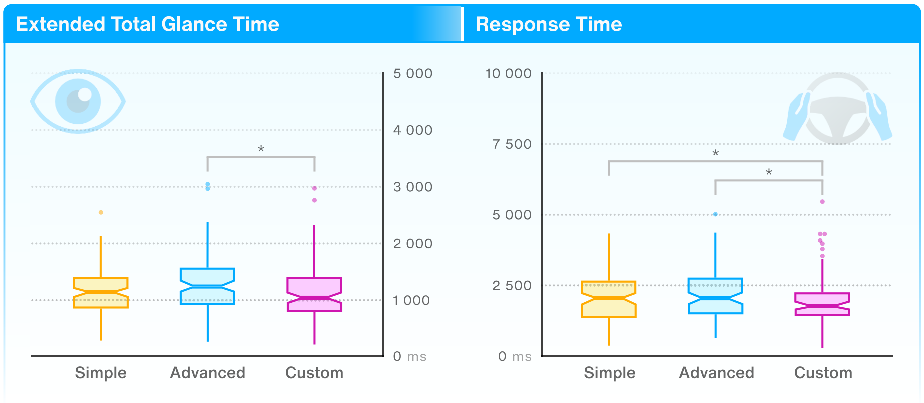

Figure 4.7 Boxplots with 95% CI (notch) of drivers' extended total glance times (xTGT; left) and response times (RT; right) for the speed limit task (1b) depending on the HMI and system speed range used. Points out of the boundaries of each boxplot are shown.

Indeed, when drivers had to set the target speed to the posted speed limit (**Figure 4.7**), they looked at their instrument panel for 198 ms longer while using the *advanced* HMI than when using the *custom* HMI ($\beta = -136.40$, 95% CI [−259.90, −12.90], $p = .03$) and also took 275 ms longer to set their target speed ($\beta = -227.52$, 95% CI [−430.65, −24.38], $p = .03$). At least two explanations can be raised: ① the strip used for the *advanced* HMI troubled drivers during this task since, as denoted before, it could be difficult to determine the speed limit, and/or ② the contrast of the *custom* strip helped drivers locate the target speed and speed limit on their speedometer faster compared to the *advanced* HMI. Drivers also took 275 ms longer to set their target speed while using the *simple* HMI than when using the *custom* HMI ($\beta = -263.26$, 95% CI [−458.75, −67.78], $p < .01$). Altogether, these results could suggest that the *custom* strip helped drivers appreciate the distance between the current target speed and the speed limit and consequently plan the necessary number of presses, either or both by easing the acquisition of the speed limit and the target speed.

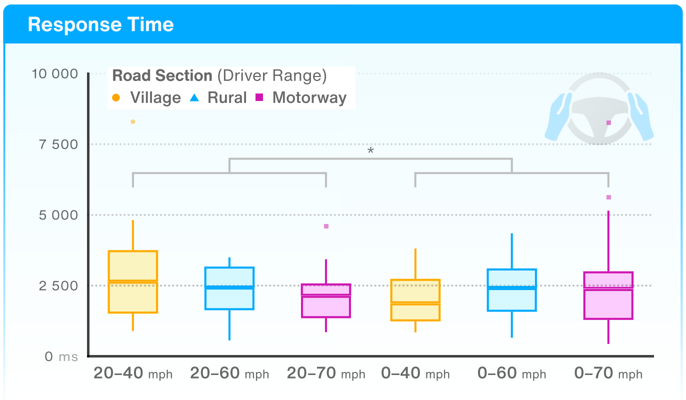

Figure 4.8 Boxplots of drivers' response times (RT) for the speed task (1a) depending on the system (i.e., without or with stop and go) and driver speed ranges of the custom strip (i.e., road section). Outliers are shown.

Regarding the results from our second statistical model, designed to compare the influence of the size of the custom strip on the xTGT and RT, the only significant comparison for the speed decrement task 1a was the interaction between system range and driver range on the RT (β = 648.44, 95% CI [2.28, 1294.59], p = .05), shown on **Figure 4.8**. This interaction suggests that the difference between the village and motorway sections (limited to 40 and 70 mph respectively) was different between the limited-range and full-range ACC conditions (i.e., without and with stop and go respectively). While increasing the range of the strip from 20-40 mph to 20-70 mph helped drivers execute the task faster (median: 2640 ms to 2124 ms respectively), increasing it from 0-40 mph to 0-70 mph of range impaired drivers' performance (median: 1866 ms to 2361 ms) when drivers needed to decrease the target speed previously set at the speed limit.

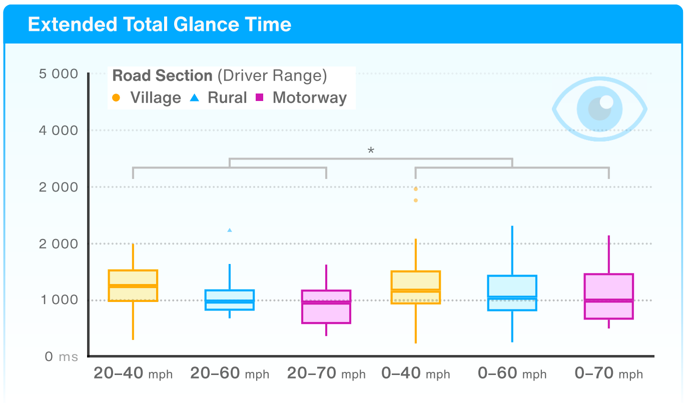

Figure 4.9 Boxplots of drivers' extended total glance times (xTGT) for the speed limit task (1b) depending on the system (i.e., without or with stop and go) and driver speed ranges of the custom strip (i.e., road section). Outliers are shown.

Finally, during the speed increment task 1b, there was an effect of the strip size on the xTGTs, with a significant difference between the village and motorway sections (limited to 40 and 70 mph respectively). Surprisingly, drivers looked at the HMI for 291 ms longer during the village section, at a lower speed (β = −150.36, 95% CI [−276.35, −24.38], *p* = .02). Given that no differences were observed in the RTs, we can hypothesise a behavioural adaptation (e.g., Carsten, 2013) where drivers looked at their HMI for shorter periods on the highway because they were simply going faster (**Figure 4.9**) and that this was not an effect of the strip itself. However, a second possibility is that the current set speed on the *custom* strip might have been more difficult to find in the village section given that the light-blue part of the strip was smaller and consequently less attractive for the eyes.

To summarise the results observed during the two speed tasks (1a and 1b), it seems that the *custom* strip improved some of the aspects for which it was designed, while overall, it presents some limitations compared to the other two HMIs. For instance, the strip could be efficient in quickly communicating the current speed limit and, potentially, planning the necessary actions to match this speed, while being as much or less efficient as the other HMIs when drivers needed to reach a specific target speed below the speed limit. As we suggested previously, this could be due to the lack of a written speed on the *custom* HMI but does not confirm whether, alone, the *custom* strip could be more efficient than a simple arrowhead or the *advanced* strip for this particular task. The reason we included both tasks 1a and 1b was that we suspected that drivers could opt for different strategies while performing them but also because the amount of visual support provided by the speedometers differs between these two tasks. A good design therefore for drivers to set the target speed of an ACC system would seem to be a strip like the one used for the *custom* HMI while having the target speed written on an accessible location of the interface like the *simple* or *advanced* HMIs. Accordingly, and only based on behavioural data, we would suggest avoiding strips like the one used for the *advanced* HMI.

B. Setting the headway distance

Figure 4.10 illustrates the distribution of drivers' xTGT and RT in this task.

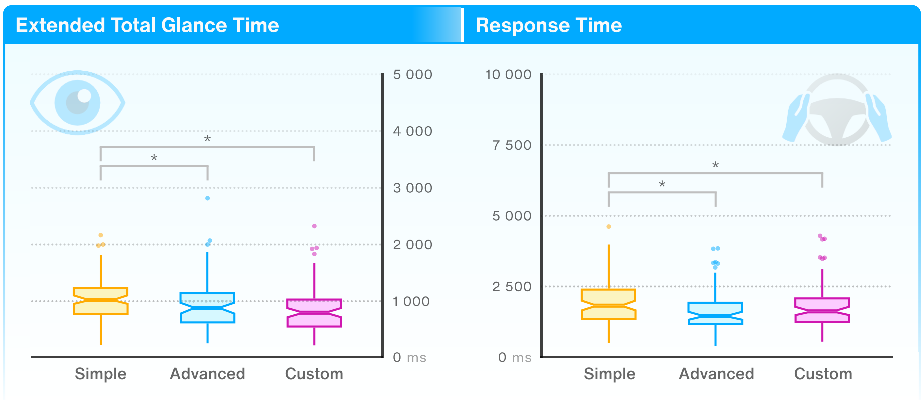

Figure 4.10 Boxplots with 95% CI (notch) of drivers' extended total glance times (xTGT; left) and response times (RT; right) for the headway task (2) in the three HMI conditions. Outliers are shown.

When setting their headway distance, drivers spent more time looking at the *simple* HMI than at the *advanced* HMI (β = 87.10, 95% CI [1.44, 172.76], p = .05) or than at the *custom* HMI (β = 178.20, 95% CI [87.96, 268.42], p < .001). Drivers also took the most time to set the said headway distance when using the *simple* HMI than when using the *advanced* HMI (β = 349.86, 95% CI [136.55, 563.16], p = .001) or the *custom* HMI (β = 203.14, 95% CI [6.26, 400.00], p < .05). However, while the difference in time spent looking at the HMI between *simple* and *custom* was bigger than between *simple* and *advanced*, the opposite was observed when comparing the response times: drivers were able to set their headway distance more efficiently while using the *advanced* HMI than when using the other two. It seems the bigger vertical design used for the *custom* HMI was good for drivers to quickly grasp the current set headway distance, but that the horizontal design used for the *advanced* HMI was associated with faster manual interactions. This could be in line with what (François et al., 2019) observed when comparing the efficiency of different designs of strip-shaped speedometers. The authors found that horizontal strips (linear or curved) were more efficient overall than vertical ones for absolute speed reading (e.g., “the current speed is 23 mph”) and relative speed reading, as they termed it, that is indicating in which quarter of the strip the current speed was in (e.g., “the first quarter”, “the second”, *et cætera*). This could be due to how reading is almost exclusively carried horizontally from left to right across languages. Therefore, this effect might be mitigated among Japanese readers for instance who are used to downwards reading as well as rightwards reading (Obana, 1997), while the observed visual advantage of the custom HMI could be due to the size of the graphical elements. In summary, bigger visuals (to a reasonable extent) are more usable than smaller ones, and the more visuals may be consistent with how drivers are used to reading, the more usable it might be; more research on the topic would be necessary. Therefore, our recommendation would be to not use the symbol as a way of setting an ACC system’s set headway.

C. Identifying the system’s mode

Participants’ answers were verbal, and consequently, the efficiency of each design was only evaluated by the time spent looking at the HMI. **Figure 4.11** shows the TGT in all three conditions when no lead vehicle was detected by the system (i.e., conventional CC). The first author manually coded from the video recordings that drivers, in 92% of cases, responded in only one isolated glance, 6% in two consecutive glances, and 2% in three consecutive glances.

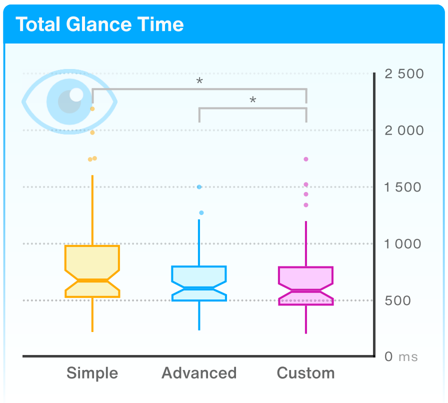

Figure 4.11 Boxplots with 95% CI (notch) of drivers' total glance times (TGT) for the mode awareness task (3) in the three HMI conditions. Outliers are shown.

We compared the *simple* HMI (i.e., hollow symbol) to the other two HMIs (i.e., a grey symbol for the *advanced* and an absent lead vehicle on the assistance graphic for the *custom*). We only found that the hollow symbol (*Simple*: $\tilde{x}$ = 672 ms) was less efficient than the other two options (*Advanced*: $\tilde{x}$ = 600 ms; *Custom*: $\tilde{x}$ = 580 ms) to symbolise the absence of a lead car (*HMI* Ψ_1: β = 110.71, $p < .01$; *HMI* Ψ_2: β = 131.63, $p < .001$).

D. *Mental effort and overall demand*

A mixed-effects gamma regression on the rating scales of mental effort (RSME) scores revealed a slight advantage of the *custom* HMI ($\bar{x}$ = 37.6) over the *simple* ($\bar{x}$ = 43.3; β = −8.4, p = .003) and *advanced* HMIs ($\bar{x}$ = 41.4; β = −9.64, $p < .001$). The participants thus rated the *custom* HMI as slightly less mentally demanding than the other two HMIs. No differences were found after performing a non-parametric Friedman test on the raw task load index (R-TLX) scores, χ^2 (2, N = 24) = 1.3, p = .52. In short, the differences between the design choices appeared to have only a minor impact on the subjective mental workload of drivers, therefore, we will not discuss it further.

2. Overall usability

A. *System Usability Scale (SUS)*

A non-parametric Friedman test showed no differences between the three HMIs in terms of their SUS scores, χ^2 (2, N = 24) = 0.6, p = .74.

B. *Semi-directed interviews*

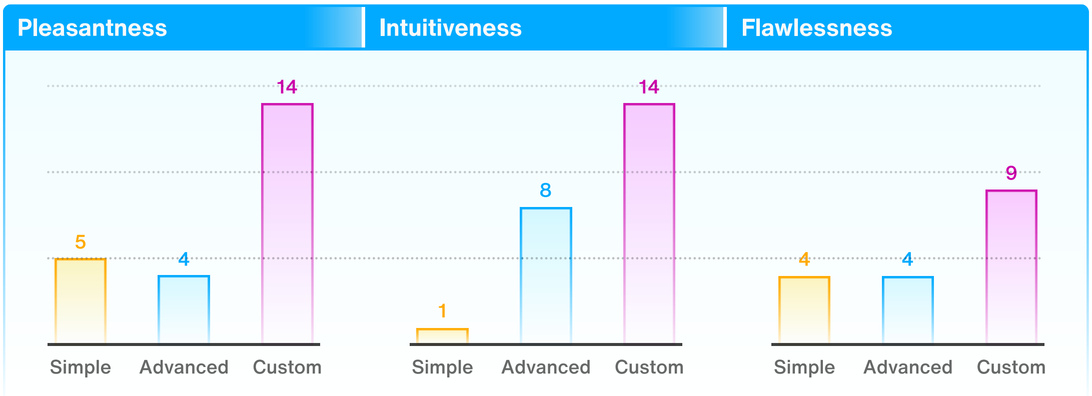

Figure 4.12 Number of drivers who elected each HMI as the most pleasant, intuitive, or flawless during the interviews.

Overall, the *custom* HMI was preferred by drivers for its pleasantness, intuitiveness, and flawlessness, that is, preventing them from making errors (**Figure 4.12**). However, five drivers could not decide between each HMI for this last aspect and were not forced to choose. All three HMIs were considered memorable enough to remember how to use them after an undefined period of non-use, although, asking drivers to judge this aspect after using each HMI for and within such a short amount of time was perhaps unrealistic. Then, all three HMIs had elements that could confuse drivers if they had to use them regularly, especially the way of indicating system mode. Although, some drivers suggested that this could be especially relevant while learning how to use an HMI. All questions considered, seven out of 22 drivers preferred some aspects of the *simple* HMI over the other HMIs, 10 preferred some aspects of the *advanced* HMI, and 21 drivers preferred some aspects of the *custom* HMI.

a. *Feedback on the 'Simple HMI'*

The five drivers who preferred the *simple* HMI did because of its minimalistic visuals (n = 2), its symbol integrating the headway distance, system mode, and target speed in a single place (*n* = 4), the way it showed system mode (i.e., lead vehicle detection) via a hollow car symbol (*n* = 4), and because it could be simpler to use for experienced users who already know how to use ACC (*n* = 2).

Among the other 18 drivers interviewed, however, some indicated their disliking being due to its smaller visuals (*n* = 5), its lack of intuitiveness (*n* = 1), lack of distinctiveness from a conventional CC mode (n = 1), its mental demand on the driver (*n* = 3), and its lack of visual saliency (n = 2).

b. *Feedback on the 'Advanced HMI'*

Among the positive comments gathered about the *advanced* HMI, some drivers said they liked it for its clear visuals (*n* = 2), the information being easy to find (*n* = 1), its readability (*n* = 2), its dynamic headway graphic where one car was moving away or towards the other one as the bars filled or emptied the space between the two cars (*n* = 6), the target speed being written next to the symbol (*n* = 1), and one driver pointed out that they preferred the maximum speed not to be limited as the *custom* speedometer did. This driver commented that they liked feeling in control of their vehicle, which would be challenged by such speed restrictions.

Some drivers disliked this HMI due to the poor contrast of the speed information on the speedometer (i.e., blue arrowhead on blue strip; *n* = 1), the strip range being too large and confusing as to what the target speed is (*n* = 1), the information being too dispersed across the interface (*n* = 1), and the lead vehicle on the symbol turning grey was potentially confusing for some drivers (*n* = 3). One driver also expressed being bothered by the vehicles on the headway graphic being oriented leftwards rather than rightwards.

c. *Feedback on the 'Custom HMI'*

Finally, the *custom* HMI was preferred by most drivers for being more readable than the other options, notably in peripheral vision (*n* = 11), for its more prominent (*n* = 3) and more contrasted visuals overall (*n* = 4), the presence of 'more feedback' because of the strip turning green when the target speed is being set (*n* = 2), for the bird's-eye view headway graphic being driver-centred (n = 1), and for the maximum speed being limited to the posted speed limit (n = 6).

Other drivers, however, disliked this interface for its visuals being too big (n = 2), too cluttered (n = 3), too distracting (n = 2), the target speed not being written (n = 2), the lead car on the bird's-eye view graphic being grey rather than a more salient colour (n = 3), and for the headway graphic not being as dynamic as the *advanced* HMI (n = 1). Indeed, only the bars between the two cars were removed dynamically, while the lead car did not move.

d. *Preference for single HMI elements*

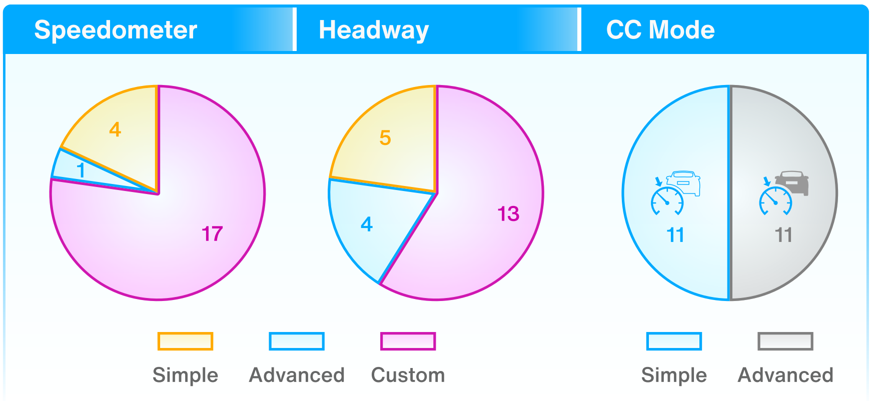

Figure 4.13 HMI elements preferred by participants during the interviews.

The *custom* strip was preferred by 17 drivers out of 22 (see **Figure 4.13**), and 14 drivers out of 15 reported they would prefer to have the speed indicated both on the speedometer and next to the ACC symbol. Thirteen (13) drivers preferred the bird's-eye view headway graphic of the *custom* HMI, while 5 drivers and 4 drivers preferred the headway being displayed on the symbol itself or a side-view graphic, respectively. Finally, the preference for the symbol's appearance was split, with 11 drivers preferring the hollow symbol and 11 drivers preferring the grey variant.

IV. Discussion

Automakers have proposed various designs for a handful of visual HMI elements intended to assist users of ACC systems in their hybrid role as supervisor and controller of the driving task. We argued that some of these designs, such as the graphical symbol being used to indicate the gap distance to maintain, could present efficiency issues and exacerbate driver distraction. We also argued about a general signifier issue, as visual HMIs often do not communicate to drivers some of the capabilities and limitations of their system, such as whether a stop-and-go function is available or not. In response, we proposed a custom speedometer that would communicate additional capabilities about the system intuitively and improve mental models of the system. We hypothesised that different HMI designs would modulate differently the time necessary for drivers to conduct routine tasks with an ACC system involving looking at their HMI. Demonstrating the impact of HMI designs on drivers' behaviour and perception would help designers of these HMIs understand how to reduce driver distraction and mode confusion. In the present driving simulator study, drivers tested and commented on three HMIs (*simple*, *advanced*, and *custom*) that were designed for the ACC system (**Table 4.1**, p. 100). To compare the efficiency of the aforementioned HMIs we analysed the total glance times (TGT) and response times (RT) gathered during four routine tasks: speed setting below the speed limit, speed setting to the speed limit, headway distance setting, and system mode reading.

1. Did HMI design affect drivers' efficiency with the system?

We observed that when setting the speed of their ACC system from the speed limit to a value below this latter, some drivers opted to rely more on the written speed below the symbol than on the graphical elements of the speedometer. Indeed, when using the *custom* speedometer—which did not present the target speed in written—drivers were longer to respond than when using the *advanced* HMI. On the other hand, when drivers increased the target speed to the speed limit, the *custom* speedometer was more efficient than the other two HMIs, possibly by being better at orienting drivers' attention toward the speed limit and the target speed and at emphasising the difference between these two values. The higher contrast introduced between the two parts of the strip and the arrowhead increased the saliency and readability of these elements and should have helped drivers orient their gaze (Carrasco, 2011; Kim et al., 2011).

Then, the smaller the visual information about the headway distance, the longer it probably took drivers to glance at it (Schuetz et al., 2019; Vertegaal, 2008) and extract it (Lindberg & Näsänen, 2003; McDougall et al., 2000): using the graphical symbol for setting the ACC system's headway distance was the least usable option tested, both in terms of efficiency (TGT and RT) and preference. A side-view or bird's-eye view of the road scene on other hand, as seen on the *advanced* and *custom* HMI respectively, resulted in the shortest interactions. However, drivers largely preferred the bird's-eye view over the symbol or side-view scene.

Finally, the way of showing ACC's mode—conventional cruise control or adaptive—also influenced how efficiently this information was conveyed: using a hollow symbol was the most distractive option tested, whereas a grey symbol or an absent car on the bird's-eye view scene were both better designs. When asked for their preference between a hollow or a grey symbol, half of the drivers would rather use the first option while the other half preferred the second option. Ultimately, drivers' preferences, in this case, could not have allowed us to predict which design would be the most efficient.

In summary, this study shows that design decisions on single graphical elements, that could appear trivial at first, can improve or worsen the usability of a visual HMI, and that designers cannot rely solely on drivers' preferences or aesthetic choices.

2. Did our custom design improve drivers' mental models?

To try and make it intuitive, the custom speedometer was designed drawing inspiration from common user interface (UI) examples and the concept of affordance (Gibson, 2014; Norman, 1999) to communicate the difference between what the vehicle could do and what the driver could do. A system range changes depending on whether a stop-and-go function is equipped, which decelerates the vehicle down to a full stop in reaction to a halting lead vehicle. The strip on the speedometer, when lit blue, showed the speed range at which the system would remain active. However, when drivers were setting a new target speed for ACC, the strip would turn green and its range shrink to reflect the speed that the driver could choose to set (**Figure 4.4**, p. 101).

Only four out of 12 drivers in the stop-and-go condition were able to understand that the *custom* speedometer was showing both a system and a driver speed range. Expectedly, none of the drivers in the other group could understand that this was the case since both strips' ranges were identical in size; they only saw the change of colour as feedback to their action. Seemingly, it remained unintuitive however for at least two drivers within each group to have a driving-assisted system not being able to come to a halt automatically if the situation required, as these drivers immediately assumed the vehicle would be full range. Nonetheless, we cannot firmly posit that the *custom* speedometer design intuitively communicated the system's capabilities and limitations, although a third of the drivers concerned were able to verbalise their mental model. Exposing drivers to a traffic jam, or a lead vehicle decelerating below the minimum driver speed, would have allowed us to assess how the design could have changed drivers' behaviour or not. We would expect drivers in the no-stop-and-go condition to react earlier and more often than the drivers in the stop-and-go condition.

3. Limitations

The present research was conducted with limited time available during the COVID-19 pandemic, potentially discouraging a part of the population to partake and preventing the recruitment of more participants due to lockdown measures. The resulting sample of 23 drivers may be considered relatively small when compared to other simulator studies. Nonetheless, the conditions' order was balanced. multilevel analysis normally reduces Type I and II errors (Arregle et al., 2006; Matuschek et al., 2017; Preacher et al., 2011), and median regression, as mentioned previously, is more robust to outliers than other types of linear regressions (John, 2015). Although one would consider the results to be not generalisable, we believe that our results are still important as they show that design differences can have observable repercussions on usability, notably in terms of visual attention. This should encourage the production of more research on the topic and encourage designers to be mindful of their design choices.

Secondly, the eye-tracker was often tedious to calibrate or keep calibrated depending on participants, which resulted in many trials being excluded from the analyses. Additionally, the lack of precision prevented us from looking back at the data to see in which trials exactly drivers used the written target speed or not.

Finally, interviewing demands training and experience that the present researcher did not have. Because of this, we cannot rule out the possibility that biased questions or body language cues were unconsciously presented to the drivers during the interviews (Dumas & Salzman, 2006).

4. Future research

In our previous research, we invited drivers to design and evaluate graphical symbols for the lane-centring control (LCC) and ACC systems (Perrier et al., 2019, 2021). The results showed a great confusion between the symbols for lane departure prevention (LDP) and LCC, and we hypothesised that this was due to the design of the LDP symbol. We also had found that the ACC symbol used with the simple HMI in the present research was the best for drivers to deduct or recognise an ACC system.

However, we hereby observed that this symbol was not a good option to set the time gap to maintain between one’s own vehicle and the leading one. Finally, vehicles equipped with L3 automated lane-keeping systems (ALKS) are expected to enter the market in 2022 and no standard symbol has been advocated yet. This arrival expands furthermore the number of systems and symbols available in our vehicles, and we should ask ourselves how this will impact drivers.

In our next research, we will investigate in a driving simulator how the graphical symbols associated with ADASs of different levels of automation can help or hinder drivers' understanding and familiarisation with these systems.

V. Conclusion

The objectives of this research were to demonstrate how small design decisions could promote driver distraction and to call for more research on the topic to help the development of design guidelines that apply to driving-assisted vehicles. It is important to accommodate first and regular users in their familiarisation with a new vehicle, as well as guarantying a safe and satisfying experience to all drivers throughout their use. Increasing consistency across vehicles through standardisation is an essential step towards this end, and the UCD approach has proven to be a reliable tool for researchers. Although drivers' preferences should not prevail over safety, they can still guide design by complementing quantitative data.

Design recommendations

We hope that the design recommendations summarised below (**Figure 4.14**) will help users of ACC in their supervisory and controller roles, by improving HMIs' usability and reducing driver distraction.

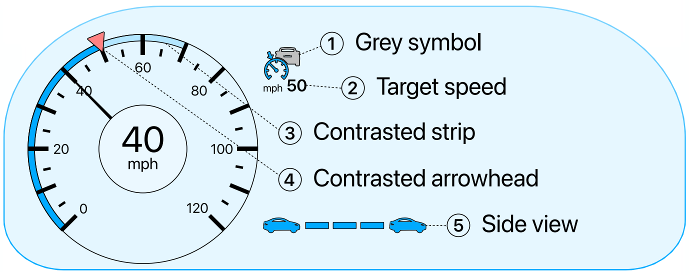

Figure 4.14 Recommended graphical HMI elements for SAE L1 assisted driving vehicles.

- ACC's conventional mode should be indicated by a symbol readable enough for all sights; avoid poor contrasts and too fine details for the naked eye (e.g., prefer a plain green and grey symbol to a monochrome hollow symbol for instance).
- ACC's target speed should always be at least written.
- If a pointer is used to indicate ACC's target speed on the speedometer, consider joining it with a coloured strip.
- If a strip and pointer are used on the speedometer to indicate the target speed, consider having two strip sections, with...
    - the section below the target speed ranging from the minimum system's speed to the target speed,
    - the section above the target speed ranging from the target speed to the speed limit,
    - both sections contrasting to show how much of the system's potential is at use and how much is left for drivers to manipulate with,
    - the pointer indicating the target speed should contrast with the strip (e.g., red on green).
- ACC's headway distance should not be set via the system's graphical symbol.

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Appendices

Regression tables

Setting the target speed

Appendix 4.1 Fixed effects from the first mixed-effect median regression model on the results of the speed task (1a). Symbols: '•' for $p \leq .1$' and '*' for $p \leq .05$.

Extended Total Glance Time (xTGT)							
Fixed effects ($\tau = .5$)	**β**	***SE* β**	**CI 95%**			***p***	
(Intercept)	196.36	(86.67)	25.89	–	366.83	.02	*
HMI Ψ_1: Simple | Custom	77.82	(75.64)	−70.95	–	226.59	.30	
HMI Ψ_2: Advanced | Custom	86.22	(80.32)	−71.75	–	244.20	.29	
Number of Glances	663.01	(68.16)	528.97	–	797.06	< .001	*
Trial Number	0.82	(0.72)	−0.59	–	2.23	.21	
Response Time (RT)							
Fixed effects ($\tau = .5$)	**β**	***SE* β**	**CI 95%**			***p***	
(Intercept)	805.41	(230.26)	351.47	–	1259.35	< .001	*
HMI Ψ_1: Simple | Custom	167.49	(115.47)	−59.62	–	394.60	.14	
HMI Ψ_2: Advanced | Custom	269.06	(133.17)	7.15	–	530.96	.04	*
Speed Decrement	−127.59	(12.11)	−151.40	–	−103.78	< .001	*
Trial Number	−4.78	(1.93)	−8.59	–	−0.97	.01	*

Appendix 4.2 Fixed effects from the second mixed-effect median regression model on the results of the speed task (1a). Symbols: '·' for $p \leq .1$' and '*' for $p \leq .05$.

Extended Total Glance Time (xTGT)							
Fixed effects ($\tau = .5$)	**β**	***SE* β**	**CI 95%**			***p***	
(Intercept)	153.86	(145.87)	−133.54	–	441.26	.29	
HMI Ψ: Custom | Advanced	−75.31	(73.51)	−220.14	–	69.52	.31	
System Range Ψ: Stop & Go	−9.69	(168.19)	−341.07	–	321.68	.95	
Driver Range Ψ_1: 40 | 70 mph	102.35	(110.93)	−116.22	–	320.92	.36	
Driver Range Ψ_2: 60 | 70 mph	85.23	(94.62)	−101.21	–	271.67	.37	
Number of Glances	735.35	(93.91)	550.32	–	920.38	< .001	*
Trial Number	1.00	(1.26)	−1.47	–	3.48	.42	
HMI Ψ × System Range Ψ	−11.00	(172.34)	−350.57	–	328.57	.95	
System Ψ × Driver Range Ψ_1	36.41	(216.50)	−390.16	–	462.97	.87	
System Ψ × Driver Range Ψ_2	33.49	(145.60)	−253.38	–	320.40	.82	
Response Time (RT)							
Fixed effects ($\tau = .5$)	**β**	***SE* β**	**CI 95%**			***p***	
(Intercept)	913.64	(244.28)	432.35	–	1394.93	< .001	*
HMI Ψ: Custom | Advanced	−249.73	(152.24)	−547.69	–	50.23	.10	
System Range Ψ: Stop & Go	−131.17	(186.05)	−497.73	–	235.39	.48	
Driver Range Ψ_1: 40 | 70 mph	171.67	(175.82)	−174.75	–	518.08	.33	
Driver Range Ψ_2: 60 | 70 mph	136.64	(156.75)	−172.20	–	445.48	.38	
Speed Decrement	−130.77	(13.77)	−157.89	–	−103.65	< .001	*
Trial Number	−5.28	(2.57)	−10.35	–	−0.22	.04	*
HMI Ψ × System Range Ψ	7.86	(318.30)	−619.28	–	635.01	.98	
System Ψ × Driver Range Ψ_1	648.44	(327.95)	2.28	–	1294.59	.05	*
System Ψ × Driver Range Ψ_2	279.02	(300.82)	−313.68	–	871.71	.35	

Appendix 4.3 Fixed effects from the first mixed-effect median regression model on the results of the speed limit task (1b). Symbols: '·' for $p \leq .1$' and '*' for $p \leq .05$.

Extended Total Glance Time (xTGT)							
Fixed effects ($\tau = .5$)	**β**	***SE* β**	**CI 95%**			***p***	
(Intercept)	536.16	(74.48)	389.74	–	682.58	< .001	*
HMI Ψ_1: Simple | Custom	−19.83	(67.02)	−151.58	–	111.92	.77	
HMI Ψ_2: Advanced | Custom	−136.40	(62.82)	−259.90	–	−12.90	.03	*
Number of Glances	413.72	(41.20)	332.73	–	494.72	< .001	*
Trial Number	0.63	(0.93)	−1.19	–	2.45	.50	
Response Time (RT)							
Fixed effects ($\tau = .5$)	**β**	***SE* β**	**CI 95%**			***p***	
(Intercept)	1328.78	(118.40)	1096.01	–	1561.55	< .001	*
HMI Ψ_1: Simple | Custom	−263.26	(99.43)	−458.75	–	−67.78	< .01	*
HMI Ψ_2: Advanced | Custom	−227.52	(103.33)	−430.65	–	−24.38	.03	*
Speed Increment	73.97	(8.76)	56.74	–	91.20	< .001	*
Trial Number	−3.88	(0.90)	−5.66	–	−2.10	< .001	*

Appendix 4.4 Fixed effects from the second mixed-effect median regression model on the results of the speed limit task (1b). Symbols: '•' for $p \leq .1$' and '*' for $p \leq .05$.

Extended Total Glance Time (xTGT)							
Fixed effects ($\tau = .5$)	**β**	***SE* β**	**CI 95%**			***p***	
(Intercept)	500.24	(147.17)	210.43	–	790.26	< .001	*
HMI Ψ: Custom | Advanced	143.50	(68.93)	7.77	–	279.23	.38	
System Range Ψ: Stop & Go	112.23	(138.34)	−160.19	–	384.64	.42	
Driver Range Ψ_1: 40 | 70 mph	−150.36	(63.98)	−276.35	–	−24.38	.02	*
Driver Range Ψ_2: 60 | 70 mph	−3.69	(77.59)	−156.47	–	2149.10	.96	
Number of Glances	405.84	(63.93)	279.95	–	531.73	< .001	*
Trial Number	0.26	(1.33)	−2.37	–	2.89	.85	
HMI Ψ × System Range Ψ	−88.53	(157.22)	−398.12	–	221.07	.57	
System Ψ × Driver Range Ψ_1	179.62	(120.14)	−56.97	–	416.21	.14	
System Ψ × Driver Range Ψ_2	178.09	(143.43)	−104.36	–	460.54	.22	
Response Time (RT)							
Fixed effects ($\tau = .5$)	**β**	***SE* β**	**CI 95%**			***p***	
(Intercept)	1199.54	(197.39)	810.83	–	1588.25	< .001	*
HMI Ψ: Custom | Advanced	211.55	(115.30)	−15.50	–	438.60	.07	•
System Range Ψ: Stop & Go	233.16	(213.07)	−186.42	–	652.74	.28	
Driver Range Ψ_1: 40 | 70 mph	−38.97	(105.87)	−274.44	–	169.51	.71	
Driver Range Ψ_2: 60 | 70 mph	−11.05	(86.80)	−181.98	–	159.88	.90	
Speed Increment	68.68	(10.24)	48.52	–	88.85	< .001	*
Trial Number	−3.16	(1.69)	−6.49	–	0.16	.06	•
HMI Ψ × System Range Ψ	−171.30	(230.99)	−626.17	–	238.56	.46	
System Ψ × Driver Range Ψ_1	−237.50	(194.20)	−619.91	–	144.91	.22	
System Ψ × Driver Range Ψ_2	−21.70	(168.50)	−353.51	–	310.11	.90	

Setting the headway distance

Appendix 4.5 Fixed effects from the mixed-effect median regression model on the results of the headway task (2). Symbols: '•' for $p \leq .1$' and '*' for $p \leq .05$.

Extended Total Glance Time (xTGT)							
Fixed effects ($\tau = .5$)	**β**	***SE* β**	**CI 95%**			***p***	
(Intercept)	404.42	(85.93)	235.47	–	573.37	< .001	*
HMI Ψ_1: Advance | Simple	87.10	(43.57)	1.44	–	172.76	.05	*
HMI Ψ_2: Custom | Simple	178.20	(45.89)	87.96	–	268.42	< .001	*
Number of Glances	348.82	(53.12)	244.38	–	453.27	< .001	*
Trial Number	0.70	0.56	−0.40	–	1.79	0.21	
Response Time (RT)							
Fixed effects ($\tau = .5$)	**β**	***SE* β**	**CI 95%**			***p***	
(Intercept)	1741.43	(104.15)	1536.62	–	1946.22	< .001	*
HMI Ψ_1: Advance | Simple	349.86	(108.48)	136.55	–	563.16	.001	*
HMI Ψ_2: Custom | Simple	203.14	(100.19)	6.26	–	400.00	.04	*
Headway Difference	26.69	(30.83)	−33.94	–	87.31	.39	
Trial Number	−1.49	(1.52)	−4.48	–	1.50	.33	

Setting the system's mode

Appendix 4.6 Fixed effects from the mixed-effect gamma regression model on the results of the mode awareness task (3). Symbol: '*' for $p \leq .05$.

Fixed effects	**β**	***SE* β**	**Student's t**	**Cohen's d**	***p***	
(Intercept)	191.80	(52.12)	3.68		< .001	*
HMI Ψ_1: Advance | Simple	110.29	(34.88)	3.16	1.03	.002	*
HMI Ψ_2: Custom | Simple	131.63	(36.70)	3.59	1.23	< .001	*
Number of Glances	518.56	(56.21)	9.23	4.87	< .001	*
Trial	−0.98	(0.39)	−2.47	−0.01	0.01	*

Chapter V

“What’s Doing What?” A Usability Comparison of ‘Affording’ and Standard Driving Automation System Symbols for SAE L1 to L3 Vehicles in a Driving Simulator

Abstract

Studies have exposed the confusion that drivers face interpreting system status when using different driving automation systems. The recent introduction of the automated lane-keeping system (ALKS), an SAE Level 3 partially automated driving system (ADS), raises the questions of whether drivers are equipped to welcome this new level of complexity in their vehicles and whether human-machine interfaces (HMIs) are appropriately designed to support drivers in their first experiences with these vehicles. In the present study, we validated symbols for the lane departure prevention (LDP) and lane centring control (LCC) systems and then used them in a driving simulator study where 28 participants drove using five systems in different motorway scenarii. We compared the number of errors and system confusions that occurred while drivers used two different sets of symbols (*standard* and *affording*) and finally interviewed drivers for them to elaborate on several aspects of their experience with the systems and symbols. Our results indicate an overall advantage of the *affording* symbols over their counterparts, which bears implications for the design of current and future driving automation systems’ symbols. We also discuss results showing a lack of usability of vehicles embarking systems up to Level 3 and what this could mean for HMI design.

I. Introduction

The United Nations Economic Commission for Europe (UNECE, 2020a) has brought together 42 countries to agree to a standardised Level 3 (L3) partially automated driving system (SAE International, 2018) under the name automated lane-keeping system (ALKS). This system, first introduced in 2022 by Mercedes-Benz as DRIVE PILOT on the automotive market, controls both longitudinal and lateral movements of a car up to 60 km/h (37 mph) on highway-like roads without requiring drivers to remain attentive, but only to be ready to take over at any requested time. Level 2 (L2) assisted driving systems such as lane centring control (LCC), in contrast, still require drivers' supervision and potentially immediate intervention and could legally be used at much higher speeds than ALKS at the time this research was conducted. Indeed, the latter system has since then been regulated and can now be used up to 130 km/h (80 mph) in Europe (SAE International, 2018; UNECE, 2022b).

The ALKS system enriches an already complex family of lane-keeping systems composed of LCC, offering sustained steering control, lane departure prevention (LDP)*** which sporadically offers steering control to prevent lane departures, lane departure warning (LDW), and emergency steering function (ESF) which automatically detects and steers the vehicle to avoid or mitigate collisions. Some of these systems can be used in unison, like in the Ford Focus 2018 (**Figure 5.1**) and are sometimes even integrated under a common label—like Tesla who have combined the ESF, LDW, and LDP systems as a single 'Lane Assist' function.

Figure 5.1 Reproduction of a Ford Focus 2018 instrument panel showing lane departure prevention (LDP), lane centring control (LCC), and adaptive cruise control (ACC) symbols next to each other.

We have previously reported the confusion that drivers faced when being exposed to the differences between the LDP and LCC systems as well as the confusion between the symbols used for these two systems (Perrier et al., 2019, 2021). Congruently, Richardson et al. (2021) suggested the

*** More commonly referred as lane-keeping assist (LKA; see Sullivan & Flannagan, 2019) need for new standard symbols for the L2 and L3 systems after surveying drivers in a focus group. Another study where drivers watched videos of an L2 system showed that drivers without training with the human-machine interface (HMI) did not know when LCC was inactive and even drivers with training sometimes could not explain why LCC was momentarily inactive (Mueller et al., 2020). That drivers can experience confusion between symbols and systems is clear, but this confusion and its behavioural consequences have not been demonstrated sufficiently ***in situ*** nor '***in simulatio***'.

Firstly, one may wonder whether drivers are ready for yet another system to be implemented in their vehicles, and secondly, whether the graphical symbols recommended by the international organisation of standardisation (ISO) and the UNECE will prevent drivers from confusing systems and help them understand these systems. To try and answer these two questions we first ideated and validated symbols for LDP and ALKS during an online survey with 71 drivers. We then tested two sets of symbols ('*standard*' and '*affording*') with 29 drivers in a low-fidelity fixed-base driving simulator. Before delving into the methods and results of this research, we will first examine the role of mental models and how drivers form them, as well as their relation to affordances, the actions that are available to the driver (Gibson, 1979), and how these may help the design of icons that help the recall of said mental models.

1. Mental models

A. *Drivers' mental models of driving automation*

First, it is worth acknowledging the discrepancy that exists between the hierarchies of automation levels established by organisations such as the SAE (2018), and how drivers may actually think of automated driving. Rather than six levels of automation, drivers may think of automation as three categories of driving assistance systems. Homans et al. (2020) argue that drivers would think of SAE levels 0 and 1 as none to low automation, levels 2 and 3 as medium automation, and levels 4 and 5 as high to very high automation. Zacherl et al. (2020), on the other hand, found that drivers would rather group driving automation systems—such as LDP, or ACC and LCC—into three categories: information to the driver, assisted to automated driving, and autonomous driving. It is therefore unsurprising to observe mismatches between the conceptual models of driving automation systems, how engineers technically designed the systems, and drivers' mental models, how drivers imagine the systems work (Norman, 1983). Indeed, Strand et al. (2011) reported that their participants comprehended several systems with a common function (e.g., forward collision warning [FCW], distance assist, and ACC) as being only one system with different functions.

To paraphrase Donald Norman (1983, p. 7): "[mental] models need not be technically accurate (and usually are not), but they must be functional" and allow the safe usage of a system. This becomes an important challenge with driving automation systems as misunderstanding how a system works can lead to mistakes, inappropriate use (Parasuraman & Riley, 1997; Sarter & Woods, 1995; Stanton & Salmon, 2009), and potential injuries or fatalities. Studies have shown how drivers unaware of an ACC system's limitations could potentially exhibit hazardous behaviours (Dickie & Boyle, 2009), or how drivers using ACC were likely to speed by setting a target speed over the speed limit, judging that the system was safer than themselves (Monfort et al., 2021; but see Varotto et al., 2022 for a counterexample).

To summarise, the way automation is conceptualised by designers appears to be unintuitive for drivers and instructing these latter to form accurate and safe mental models is a major challenge. Understanding how mental models form can therefore be essential to better instruct drivers.

B. How do mental models form?

Our primary source of knowledge when trying to understand our environment is through analogies (Bar, 2007; Collins & Gentner, 1987), that is, associating information to a new concept based on its similarity with a concept already acquired. As such, users' technical background and previous experiences with similar systems will constrain their mental modelling when faced with new systems (Norman, 1983). Yet another crucial means of forming mental models is through interactions. What a driving automation system does in place of the driver determines how the system will be perceived. For instance, LCC being correctly perceived as having more capabilities than LDP although both systems' goals may seem similar: keeping the car in the lane (Sullivan & Flannagan, 2019). But what the driver does while using a driving automation system will also influence their understanding and expectations of the system: keeping their hands on or off the steering wheel while using LCC, for instance (Landry et al., 2020). In other words, the set of actions that are perceived available to the driver when occupying the driver's seat, their *affordances* (see Gibson, 1979, Chapter 8), will determine which mental models are recalled and maintained in working memory during the drive (Jones et al., 2011). Additionally, what a system offers to the driver by automating certain aspects of the driving task can be termed *use* or *experience affordance* (Pucillo & Cascini, 2014).

There is a limit, however, to how much drivers can learn through interaction. Some drivers accustomed to driving with ACC have reported getting confused when using the conventional cruise control (CC) and braked too late to a decelerating lead vehicle, thinking the system would slow down on its own (Strand et al., 2011). One explanation given by the authors was that the lack of differences between the experiences of driving with CC and ACC had caused mode confusion. Manufacturers, therefore, should be careful not to rely too heavily on drivers to learn by themselves as their abilities to deduct a system's limitations remain limited and may lead to inappropriate behaviours before they even form accurate mental models (Aziz et al., 2013). Car manuals tend to be unused and poorly adapted to the everyday driver (Oviedo-Trespalacios et al., 2021), most of the time even incomplete (Capallera et al., 2019). Moreover, current systems' names and symbols can confuse or mislead drivers (Abraham et al., 2017; Helman & Carsten, 2019; Nees, 2018; Perrier et al., 2021; Teoh, 2020). Manufacturers, therefore, may want to design HMIs that remain intuitive to allow analogies and that appropriately reflect the driver-car dyad's interactions.

2. Graphical symbols

Graphical symbols can easily communicate complex concepts (Gittins, 1986; Womack, 2005) and improve the readability of an interface (e.g., Job et al., 1992; Liang et al., 2018; Ojanpää, 2006; Rettenmaier et al., 2020). The use of well-designed symbols in vehicles equipped with driving automation systems[†††] can improve the usability of these vehicles by reducing the necessity for initial training in some cases, that is, increasing intuitiveness (Huang et al., 2019; Reddy et al., 2009; Stenberg, 2006), increasing the memorability of using these vehicles (Chajadi et al., 2020; Sami Uddin & Gutwin, 2021), and increasing drivers' efficiency with the car by preventing confusion with other driving automation systems' symbols.

A. Which symbols are recommended?

Standardising symbols is an effective means of increasing systems' usability and therefore their acceptance. However, manufacturers tend to deviate from the recommended symbols to adopt their own designs (see Perrier et al., 2021), and no symbol for LCC has been regulated yet. Some manufacturers, therefore, decided to opt for the LKA/LDP symbol (**Figure 5.2**), then risking confusion between both systems.

The only information given for LCC[‡‡‡] in the UN Regulation N°79 (UNECE, 2020a, p. 16) is that "the optical signals [for all lane-keeping systems[§§§]] shall be easily distinguishable from each other (e.g., different symbol, colour, blinking, text)", but nothing specific to LCC systems. Regarding the newest ALKS, one can read in the UN Regulation N°157 (UNECE, 2021, p. 14): "The optical signal shall contain an unambiguous indication including: (a) A steering control or a vehicle, with an additional 'A' or 'AUTO,' or the standardised symbols in accordance with UN Regulation No. 121." There exists, however, no symbol yet for either ALKS or LCC in the aforementioned UN Regulation N°121 (UNECE, 2015, 2017, 2018b, 2020b). Moreover, although the cited text specifies the need for an "unambiguous" optical sign (i.e., a symbol), some drivers during a previous

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[†††] Any system capable of L1 to L5 driving automation. Not to be confused with automated driving system, or ADS, referring to L3 to L5 driving automation systems specifically (SAE International, 2021).

[‡‡‡] Designated as an automatically commanded steering function of category B2 (ACSF-B2) in the UN Regulation N°79 (UNECE, 2018a).

[§§§] Which includes LDW, LDP, LCC, ALKS, and more.

workshop expressed the ambiguity of only having a steering wheel, pedals, or a car as a symbol (Perrier et al., 2019).

Figure 5.2 ISO standard symbols for CC, ACC, and LKA, hereby referred to as lane departure prevention (LDP).

B. Which symbols do drivers need?

We hypothesised in Perrier et al. (2021) that the confusion observed between LDP and LCC might have been due to the LDP standard symbol rather than the poor design of LCC's symbols. We argued that although the LDP system detects unintentional lane exits one side of the lane at a time, the symbol depicts both lines of the lane and lacks any action or affordance symbology. This may be an issue as we found that drivers tended to ideate and prefer symbols that reflected (a) the actions of the car or driver while a particular system was active, or (b) the signifiers (i.e., visual cues) used by drivers to infer the affordances present in the environment (Perrier et al., 2019). As such, more drivers preferred an ACC symbol where the headway distance between the driver's car and the lead vehicle was depicted. Not only did they prefer such a symbol, but also was it more accurately described as an ACC system than the standard symbol shown in **Figure 5.2**. Moreover, drivers during the workshop preferred an LCC symbol where hands were depicted on the steering wheel for representing a hands-on system. Although hands increased the confusion with an LDP system in the survey previously mentioned, the survey did not account for the ALKS. We hereby hypothesise that affordance-based symbols should benefit the recognition of the systems activated, the development of mental models, and the usability of vehicles equipped with driving automation systems.

3. Summary & objectives

With the arrival of ALKS and the consequent broadening of the lane-keeping systems' family, our cars are in need of an ecosystem of symbols that would help prevent confusion between driving automation systems and ease the process of learning how to use vehicles equipped with driving automation systems. We hypothesise that the representation of relevant affordances matters for the development of appropriate mental models and their recall, and that standard symbols, so far, lack such information. Our research objectives were therefore to develop a suite of symbols while considering the importance of representing affordances and then compare these symbols to the recommended symbols during a driving simulation.

II. Survey: Symbol Validation

We first needed to validate *affording* symbols for LDP and ALKS, as we already had symbols for ACC and LCC for an *affording* suite (Perrier et al., 2021). Additionally, we needed to validate a symbol for ALKS for the *standard* suite that would be based on the recommendations made by the UNECE (2021). An online survey was developed and distributed to drivers for them to judge the appropriateness and suitableness of the symbols generated during an ideation phase.

1. Methods

A. Respondents

After approval from the University of Leeds Research Ethics Committee, sixty-seven French and four British drivers aged between 20 and 79 years old ($\bar{x}$ = 34.07, s = 10.36) responded to our online survey. All respondents held valid driving licenses.

B. Ideation phase & materials

The main author first ideated symbols for the LDP and ALKS systems based on an agreed list of keywords and then reviewed the symbols with the other authors (see **Appendix 5.1**). Four symbols were generated for the LDP system and 13 symbols for the ALKS. The standard LKA symbol (see **Figure 5.2**) and the LDW symbol were added to the four other symbols for LDP. Finally, four symbols were added to the other 13 ALKS symbols based on the UN Regulation N°157 (see p. 142) and on the symbol most largely used for LCC by manufacturers.

C. *Survey design and procedure*

The online survey was designed and administered on Qualtrics' software (Qualtrics, Provo, UT). The survey was made available in two languages: English (British) and French (Metropolitan). It was advertised on social media (Facebook, Twitter, LinkedIn) and no compensation was promised to the respondents.

Respondents were first asked for some demographic information, driving experience, and whether they already knew the symbols or systems for the blind-spot monitoring (BSM), FCW[****], LDW, LKS, CC, and ACC systems.

Respondents were then given four descriptions of driving automation systems, namely ACC, LDP, LCC, and ALKS (see **Appendix 5.2**). They were then shown the six candidate symbols for LDP and asked to categorise each of them as 'appropriate' or 'not appropriate' for the system given its description. The same was then asked with the 17 candidate symbols for ALKS, and then again for the same 17 ALKS symbols but captioned 'AUTO' as recommended in the UN Regulation N°157.

Then, respondents were told that the symbols that they just rated could appear alongside the symbols of other systems, and they were shown the symbols and names for the FCW, BSM, LDW, CC, ACC and LCC systems. Then, they were asked to choose the symbol that they thought would be best for LDP, bearing in mind that this symbol should be distinct enough from the other symbols while allowing drivers to understand what the system does.

[****] Reminder: forward collision warning (FCW), lane departure warning (LDW), and lane keeping system (LKS).

The same procedure was repeated twice for ALKS with only the 13 symbols that had been ideated: once without the caption and once with the caption 'AUTO'. A third suitableness test asked respondents to choose the symbol that they judged was the most suitable among the four remaining symbols labelled as recommended (see **Appendix 5.1**). Each time, drivers could explain their choice if they wanted.

Finally, we asked respondents to choose the symbol that they would prefer to use for ALKS among the three symbols that they had elected previously: ideated, ideated with caption, and recommended with caption. This additional test will be referred to as 'Preferability' in the 'Results' section.

2. Results

A. Lane departure prevention

Table 5.1 shows the results for this system where we can see that the symbol depicting a car ricocheting on a dashed lane marking was the symbol most often judged as appropriate (80% of respondents) as well as being the symbol most selected as the most suitable to be used alongside other driving automation systems' symbols (44% of respondents). For comparison, the standard symbol for LDP (a car between two dashed lane markings) obtained a rating of 54% and 7% for appropriateness and suitableness, respectively. A one-sample Chi-square goodness-of-fit test indicates that drivers selected the most suitable symbol significantly more than the 2nd one, χ^2 (1, N = 44) = 7.36, p = .007. These statistics are consistent with the hypothesis that the standard symbol does not sufficiently represent the signifiers and affordances of the vehicle.

Table 5.1 Percentage of respondents who elected the following symbols for the lane departure prevention (LDP) system during the appropriateness and suitableness tests.

N = 71						

Appropriateness	80% (n = 57)	66% (n = 47)	55% (n = 39)	54% (n = 38)	49% (n = 35)	25% (n = 18)
Suitableness	44% (n = 31)	18% (n = 13)	17% (n = 12)	7% (n = 5)	7% (n = 5)	7% (n = 5)

B. *Automated lane-keeping system*

For the ALKS, due to the larger number of symbols tested we will only show the top 6 symbols for each test. The symbol depicting a lane with continuous markings, a steering wheel and an arrow centred in the lane and pointing forward was the one most often judged as appropriate (56%) and most often judged as the most suitable (20%) among the 17 symbols without the 'AUTO' caption (**Table 5.2**). It was however not significantly more often judged suitable than the symbol judged most suitable by 14% of drivers, χ^2 (1, N = 24) = 0.67, p = .41. Moreover, it was rarely preferred (3%) as the one symbol that respondents would use in their car when asked to choose between the ideated symbol, the AUTO symbol, and the recommended symbol that they had previously judged as the best suitable options.

Table 5.2 Results for the top 6 symbols (ideated + recommended) without the 'AUTO' caption for the automated lane-keeping system (ALKS).

						
Appropriateness (N = 71)	56% (n = 40)	48% (n = 34)	44% (n = 31)	42% (n = 30)	38% (n = 27)	38% (n = 27)
Suitableness (N = 71)	20% (n = 14)	11% (n = 8)	6% (n = 4)	14% (n = 10)	7% (n = 5)	6% (n = 4)
Preferability (N = 69)	3% (n = 2)	1% (n = 1)	0% (n = 0)	0% (n = 0)	1% (n = 1)	0% (n = 0)

The same symbol with the 'AUTO' caption was also most often judged as appropriate (65%) and as the most suitable (23%; **Table 5.3**). Slightly more than the same symbol without the 'AUTO' caption. Again, there was no significant difference between this symbol and the 2^{nd} most suitable symbol, χ^2 (1, N = 25) = 1.96, p = .16. It was however more often preferred (19%) than the same symbol without the caption (3%), and was significantly more often preferred than the symbol showing a car and a steering wheel (4%), χ^2 (1, N = 17) = 4.76, p = .03.

Table 5.3 Results for the top 6 ideated symbols with the 'AUTO' caption for the automated lane-keeping system (ALKS).

	AUTO	AUTO	AUTO	AUTO	AUTO	AUTO
Appropriateness (N = 71)	65% (n = 46)	58% (n = 41)	51% (n = 36)	49% (n = 35)	48% (n = 34)	44% (n = 31)
Suitableness (N = 69)	23% (n = 16)	13% (n = 9)	4% (n = 3)	9% (n = 6)	9% (n = 6)	7% (n = 5)
Preferability (N = 69)	19% (n = 13)	6% (n = 4)	3% (n = 2)	6% (n = 4)	3% (n = 2)	4% (n = 3)

Finally, out of the four other symbols that could be recommended by the UNECE, the symbol usually used for LCC plus a caption running 'AUTO' beneath it was by far judged as the most suitable (54%) among these four options, significantly more than the 2nd most suitable, χ^2 (1, N = 50) = 11.52, p < .001. It was also eventually preferred by 14% of respondents when asked to choose between the ideated symbol, the ideated symbol with the 'AUTO' caption, or the recommended symbol that they had previously chosen as the most suitable symbols (see **Table 5.4**).

Table 5.4 Results for the four recommended symbols with the 'AUTO' caption for the automated lane-keeping system (ALKS).

	 AUTO	 AUTO	 AUTO	 AUTO
Appropriateness ($N = 71$)	55% ($n = 39$)	44% ($n = 31$)	61% ($n = 43$)	51% ($n = 36$)
Suitableness ($N = 69$)	54% ($n = 37$)	19% ($n = 13$)	17% ($n = 12$)	10% ($n = 7$)
Preferability ($N = 69$)	14% ($n = 10$)	6% ($n = 4$)	4% ($n = 3$)	1% ($n = 1$)

3. Discussion

The objective of this survey was to ideate and validate new symbols for the LDP system and ALKS to use in a follow-up driving simulator study. The results from this survey were congruent with the hypothesis that representing affordances is important since the LDP symbol that received the best ratings indeed shows the signifiers and the action associated with the system more than the standard symbol does. As for ALKS, the symbol that received the best ratings has a very similar design to that of the symbol often used for LCC by manufacturers—showing a steering wheel devoid of hands and aligned between continuous lane markings. It has, however, an additional arrow pointing forward above the steering wheel. How drivers interpret it may vary as it was intended to represent a forward movement, but some drivers had previously ideated a similar symbol for LCC with the arrow representing the car centring itself in the lane and following this latter (Perrier et al., 2019). Yet, again, we can see how this additional information is linked to affordances and their signifiers. Our next objective was to assess how these '*affording*' symbols compared to the '*standard*' symbols and how they could concretely help drivers in their use of vehicles equipped with driving automation systems.

III. Simulator Study: Symbol Evaluation

In this study, we placed drivers into different scenarii and observed whether they would use the five driving automation systems at their disposal while complying with their respective operational design domains (ODD). We hypothesised that the '*affording*' symbols would help the development and/or maintenance of appropriate mental models and therefore prevent the occurrence of confusion and mistakes. We also investigated how the arrival of ALKS or L3 ADS vehicles would be received by drivers, notably in terms of usability. Our research questions were:

- Does one suite of symbols elicit more accurate mental models than the other?
- Is the experience acquired with one suite transferable to the other?
- What are drivers' attitudes towards each symbol suite and each symbol?
- Is using several levels of automation intuitive or confusing for drivers?

1. Material and methods

A. *Experimental Design*

a. Participants & design

After approval from the University of Leeds Research Ethics Committee, 29 participants with valid driving licenses were recruited via a mailing list. All but one drove regularly in the UK; this participant was used to driving on the left-hand side of the road in India, however, and was not excluded. All had normal or corrected-to-normal vision and hearing and received £30 as monetary compensation for their participation. The sample was composed of 10 females and 19 males between the ages of 20 and 72 years ($\bar{x}$ = 37.28, s = 14.23). The experiment had a mixed factorial design with the fixed effects being the Symbol Suite (*standard* | *affording*) as a within-subject factor and the Training Suite (*standard* | *affording*) as a between-subject factor. The dependent variable was the number of events coded as symbol confusion, mode confusion, or mental model error per driver

b. Apparatus

The research employed the University of Leeds fixed-base low-fidelity driving simulator (**Figure 5.3**) operated on a Dell PC running Windows 10 Pro, Intel Core i7 CPU (2.90 GHz) and 16 GB of RAM, using custom-made software. The visual simulation was displayed on a Dell-U4919DW UltraSharp 49” Curved Monitor (Dual 27” QHD) 5120×1440 (32:9 ratio) LED monitor, rendered at 60/75 Hz. An IPS QHD 10” 2560×1600 (16:10 ratio) LED monitor (Model: LR10QHD02) was used for providing the instrument panel and placed behind the steering wheel. Vehicle control inputs were recorded via Logitech G27 dual-motor force feedback steering wheel and pedals. Video recordings were captured via a Logitech C920 webcam mounted on a tripod behind the driver’s shoulder.

Figure 5.3 Driving simulator setup. The red buttons on the left of the steering wheel were used to control the CC and ACC control settings. The red buttons on the right were used to activate or deactivate CC/ACC (top), LDP (middle), and LCC/ALKS (bottom).

c. Driver-vehicle interface

The CC, LDP, and LCC systems were activated or deactivated by pressing and holding for 1.5 seconds the buttons on the right of the steering wheel (**Figure 5.3**). ACC and ALKS were activated or deactivated by a double-press and hold of 1.5 sec of the top and bottom buttons respectively. Activating LCC or ALKS automatically activated ACC, while deactivating ACC automatically deactivated LCC or ALKS. Equally, activating CC while LCC or ALKs were active would automatically deactivate these systems.

LDP was completely independent of the other systems. Distinctive short tunes were made for each system's activation and deactivation.

The same CC symbol was used for both HMIs since this one is consistently used across manufacturers and since no particular problem was observed in previous research. The symbols used for ACC, LDP, and LCC with the *standard* HMI (**Table 5.5**) were taken from Perrier et al. (2021). The symbol for LCC received the best ratings in this research and is already often used by manufacturers. The symbol for ALKS received the best ratings in the survey reported earlier in this very article. The ACC symbol used for the *affording* HMI was also used because it received the best ratings in Perrier et al. (2021). The LDP symbol was also validated in the survey reported in section 2, as well as the ALKS symbol. However, we decided to replace the 'AUTO' caption with a system boundary information (i.e., 'MAX40') to adhere furthermore to the direction taken for this suite of symbols, that is, conveying affordances. Similarly, contrasted hands were added to the LCC symbol to emphasise the difference between LCC and ALKS and to remind drivers of the hands-on aspect of LCC.

Table 5.5 Graphical symbol suites used for the *Standard* and *Affording* HMIs.

The HMI (see **Figure 5.4**) integrated a speedometer, a strip showing the target speed of the ACC system on the speedometer, the posted speed limit which blinked and chimed when it changed, the written target speed with the maximum target speed allowed to be set, and a dynamic 3D bird-eye view of the road scene. This 3D scene showed the ego car, lead vehicles within the same lane, real-time headway distance to the lead vehicle between 0 and 10 seconds, three bars each representing 2-

second gaps to be maintained by the ACC system, and the lane markings. These markings were white while LCC or ALKS were inactive, turned blue when any of these two systems were activated, and turned red to indicate that the vehicle could not read the markings properly in foggy conditions or when traffic cones were placed on the road.

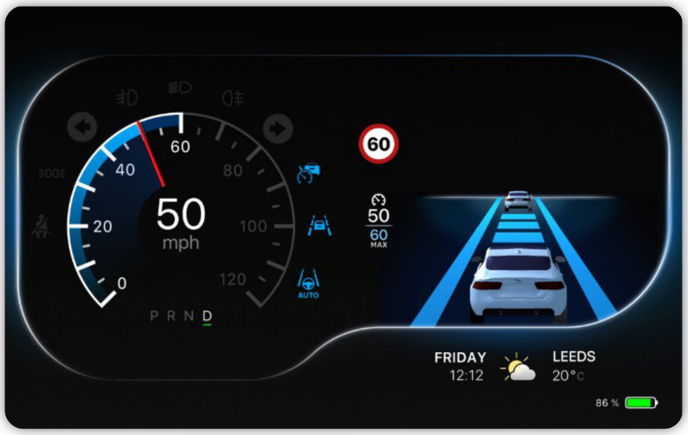
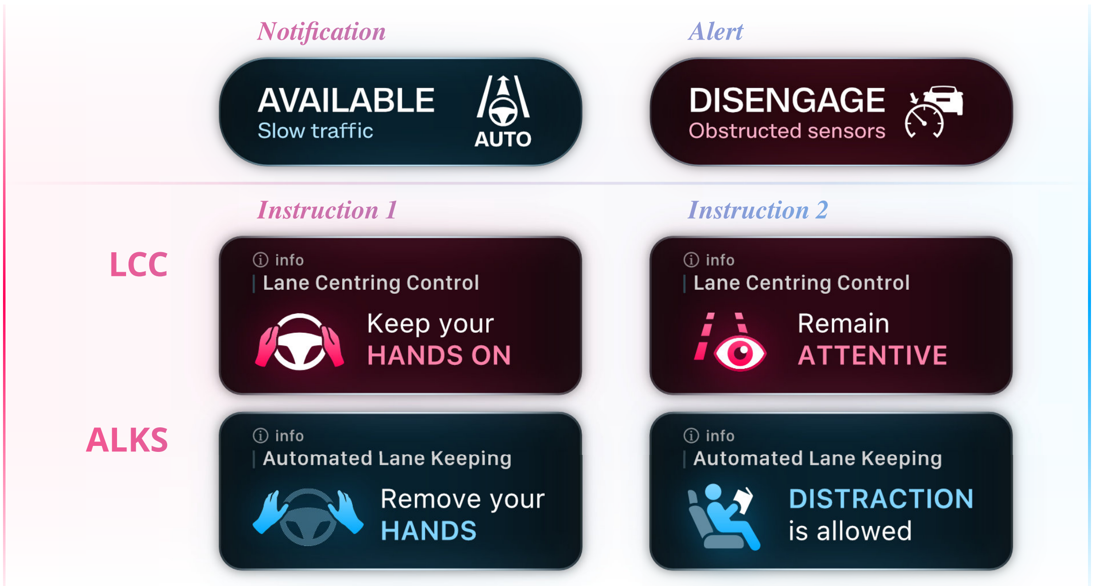


Figure 5.4 *Standard* version of the HMI used during the driving simulation. For the *affordance* version, the symbols for ACC, LDP, LCC, and ALKS were replaced.

Notifications, alerts, and instructions (**Table 5.6**) were displayed above the 3D scene view in several conditions. Firstly, the driver was notified about ALKS being available when they drove in a slow-traffic section of the driving simulation. Secondly, the driver was alerted that ACC, LDP, LCC, or ALKS needed to be disengaged due to foggy conditions or poor lane markings' visibility. Finally, instructions appeared when the driver activated LCC or ALKS to remind them of how to use the system. These notifications and alerts were displayed and sounded for as long as the criteria for their appearance were met until valid action was taken or conditions changed.

Table 5.6 Notifications, alerts, and instructions shown on the HMI.



d. Procedure

Participants received information about the experiment and safety procedures regarding the pandemic by email prior to their visit. They were welcomed at the simulator facility by the experimenter and were installed at a desk. They were first asked to fill out a consent form and then a questionnaire about their demographics and driving experience on a personal computer. They were then explained briefly what they were going to do during the study. Before starting the driving simulation, the drivers practised thinking aloud while playing a problem-solving point-and-click video game, '*Un pas fragile*' (de Courrèges, 2019). We chose this exercise for the importance of visual signifiers and context analysis in the puzzles that the player has to solve to progress through the game. The training lasted between 5 and 10 minutes depending on the participants' abilities.

Participants were then invited to sit at the driving simulator and set the distance from the seat to the pedals and the height of the steering wheel. They were then given an iPad and allowed as much time as needed to read through a document detailing the use of the five systems. Participants were free to try pressing the buttons on the steering wheel while they were reading the manual. Magnets with symbols were placed on each side of the steering wheel next to the buttons (see **Figure 5.3**, p. 151) and were replaced in between drives to match the symbols of the HMI in use. When the participant decided that they were ready, the experimenter proceeded with the practice drive. Participants were free to drive the vehicle as they wanted but the experimenter would intervene to invite participants to use each of the five systems at their disposal and made sure that they got familiar with the controls. After a practice drive of approximately 5 to 10 minutes, depending on participants' skills, the drive ended, and the experimenter invited participants to have another look at the manual.

The two experimental drives took place exclusively on a motorway and lasted approximately 17-20 minutes. Two roads were designed for the drives, their difference being the order in which certain sections would be encountered by the driver, and therefore, which driving automation system they should or should not use (**Table 5.7**). These two roads were counterbalanced between all participants.

Table 5.7 Design of both roads used during the experiment.

	1st zone	2nd zone	3rd zone	4th zone	5th zone	6th zone
Road A	Clear	Fog	Clear	Slow traffic	Works	Clear
Road B	Clear	Slow traffic	Works	Clear	Fog	Clear

The first type of road section was clear of any particular event and therefore speed was limited to 70 mph. In this section, drivers should have used LCC but not ALKS. The second type of road section had foggy weather conditions. The traffic was limited to 40 mph and only CC should have been used. An electronic gantry sign warned drivers upon entering the zone about the weather and the new speed limitation. The HMI also signalled the change of speed limit. After 5 seconds, if ACC was activated, an alert would prompt drivers to deactivate ACC due to "obstructed sensors" (**Table 5.7**). Then, if LDP was active but not ACC, an alert prompted drivers to deactivate LDP. The third type of road section was the slow traffic section, with a speed limited to 40 mph, which allowed drivers to use ALKS safely. An electronic gantry sign indicated the new speed limit due to the slow traffic. Five seconds past the gantry sign, a notification prompted drivers to activate ALKS if it was not already. This road section always led to traffic congestion, and subsequently, road works where the rightmost lane was closed, and the speed was limited to 50 mph. While driving in the middle lane, drivers were prompted to deactivate LCC or ALKS given that traffic cones were placed on the lane marking.

The sessions were video-recorded and a combination of think-aloud and concurrent probing techniques was employed. Drivers were intermittently asked to say which driving automation systems were currently active, whether other systems could have been used, and whether they understood why some systems should not be used in certain situations. Once per drive, they were also asked to explain what changed for the driver to be using LCC or ALKS.

After both experimental drives, drivers were asked to answer several questions on a computer about their experience. They were first asked to talk about their general impression and then talk about the intuitiveness and usefulness of having the five systems. Then, while still thinking aloud first, they were asked to select the symbol suite that they preferred to use, and then which of the ACC, LDP, LCC, and ALKS symbols they preferred. Subsequently, they were asked whether switching from one suite to the other was easy and whether the symbols within each suite were different enough to be recognisable. Finally, the drivers filled out their compensation forms and were thanked for their participation.

B. Data analysis

A hybrid approach was employed to code our qualitative data. A codebook of deductive codes was first created to analyse the video recordings and classify the events observed and comments made by the drivers. These codes were adapted from the definitions provided by Bredereke and Lankenau (2002), Parasuraman and Riley (1997), and Sarter et al. (1997) for mode awareness, mode confusion, mode error, misuse, automation surprise, mistrust, misuse, disuse, nonuse, mistake, and slip. While watching through the recordings, the deductive codes were revised, and additional inductive codes were added to the codebook to further analyse the qualitative data and extract important themes. The resulting codebook had a combination of process codes and value codes, that is, action-based codes and attitudinal codes respectively. It was finally restructured into three levels of codes for deeper analysis if needed: human factor, human error, and human goal. The ‘human factor’ code was the 1st level and would describe the origin of the observed event (e.g., inaccurate mental model; see **Appendix 5.3**). When applicable, the 2nd-level ‘human error’ code would describe which action was considered a mistake (e.g., pressing a button or pedal). Finally, when applicable, the 3rd-level ‘human goal’ code described what the original purpose of the driver was or whether the action executed was a simple slip (e.g., increasing the vehicle’s speed).

Given our research questions and the fact that few data had been observed for several codes, only the ‘symbol confusion’, ‘mode confusion’, and ‘inaccurate mental model’ codes were analysed statistically. Then, our data being count data and dependent within participants (i.e., repeated measures), a mixed-effect Poisson regression was considered and run in R (R Core Team, 2020) using the *lme4* (Bates et al., 2015) package. The dependent variable was the number of events coded as symbol confusion, mode confusion, or mental model error per driver. As fixed effects, we modelled the effect of the symbol suite (*Symbol Suite* Ψ: standard = –0.5, affording = +0.5) and the effect of the drive order (*Drive Order* Ψ: 1st drive = –0.5, 2nd drive = +0.5) as simple codes, two simple codes comparing the symbol confusion code to the mode confusion (*Code* Ψ_1: SC = –1/3, MC = +2/3, IMM = –1/3) and inaccurate mental model codes (*Code* Ψ_2: SC = –1/3, MC = –1/3, IMM = +2/3), and the interaction between symbol suite and drive order. As random effects, we modelled an intercept for each driver and slopes for each fixed effect. However, a singularity problem was reported by the R software, which indicated that the variance of the parameters for the random effects was null or close to 0. Reducing the statistical model by only modelling the intercepts for each driver did not fix this issue. Consequently, we opted to run a Bayesian mixed-effect Poisson regression in R using the brms (Bürkner, 2017) package as advised by Bates et al. (2022, p. 50), which resolved the issue. The regression was then checked for overdispersion, zero-inflation, goodness-of-fit, and presence of influential data. Unless stated otherwise, all statistical tests were used with a significance threshold of $\alpha = .05$.

Comparisons between symbol suites within a single drive and a single code were also run to test for single effects (e.g., a difference in the number of symbol confusions between symbol suites in the 1st drive only). These comparisons removed the dependencies between each group which allowed us to run (frequentist) Poisson regressions where only the fixed effect of the symbol suite was modelled as a simple code. The regressions were also checked for overdispersions, zero-inflation, goodness-of-fit, and influential data.

2. Results and analysis

A. RQ1: Development and recall of mental models

To investigate whether one of the two symbol suites used in the present study helped drivers develop more accurate mental models or recall these mental models more efficiently than the other symbol suite, we ran a Bayesian multilevel Poisson regression on the number of human errors committed by drivers. The results showed that there was indeed a consistently lower number of human errors made while using the *affording* suite compared to the *standard* one (*Symbol Suite Ψ*: IRR = 0.49, 95% CI [0.34, 0.72]; see **Table 5.8**). There was also a tendency for drivers to commit fewer human errors during the 2nd drive as showed by both boundaries of the confidence interval nearing a value inferior to one (*Drive Order Ψ*: IRR = 0.73, 95% CI [0.49, 1.04]). This was to be expected and would indicate a learning effect. Then, there may have a trend to observe more symbol confusion than mode confusion (*Code* Ψ_1: IRR = 0.67, 95% CI [0.37, 1.15]), but significantly more mental model errors than symbol confusions were observed (*Code* Ψ_2: IRR = 2.41, 95% CI [1.62, 3.64]). Finally, there was an interaction between symbol suite and driver order, indicating that the effect of the symbol suite differed depending on the drive (*Symbol Suite Ψ* × *Drive Order Ψ*: IRR = 0.46, 95% CI [0.21, 0.97]).

Table 5.8 Results of the Bayesian multilevel Poisson regression on human errors. ICC = intraclass correlation coefficient.

Predictors		Incidence Rate Ratios	95% Confidence Interval
(Intercept)		0.67	0.53 – 0.83
Symbol Suite Ψ		0.49	0.34 – 0.72
Drive Order Ψ		0.73	0.49 – 1.04
Code Ψ_1: Symbol vs Mode		0.67	0.37 – 1.15
Code Ψ_2: Symbol vs Mental Model		2.41	1.62 – 3.64
Symbol Suite Ψ × Drive Order Ψ		0.46	0.21 – 0.97
Random Effects			
σ^2	0.20		
τ_{00}	1.22		
ICC	0.14		
N_{ID}	28		
Observations	168		
Marginal R^2 / Conditional R^2	0.339 / 0.437		

Consequently, we used the 'hypothesis' function of the *brms* package (Bürkner, 2017) to run one-sided non-linear hypothesis tests in R to check whether the number of human errors when using the *affording* suite was lower than with the *standard* suite in the 1st and 2nd drives separately. We corrected the significance threshold by dividing it by the number of tests ($\alpha = .05 \div 2 = .025$). The results indicated that the *affording* suite in the 2nd drive was indeed associated with fewer human errors than its counterpart ($\beta = -1.10$, 95% CI [−1.71, −0.51]). However, no significant difference was observed for the 1st drive, although the upper boundary of the confidence interval approximated zero, which would indicate a trend for drivers to make fewer human errors with the *affording* suite ($\beta = -1.10$, 95% CI [−0.79, 0.17]).

So far, we have learned that the *affording* suite was overall associated with fewer human errors than the *standard* suite. There was only a trend for drivers to make fewer errors with the *affording* suite during the 1st drive, but they made significantly fewer errors during the 2nd drive with the *affording* suite. However, we still did not know whether the *affording* symbols were less confused or if they were associated with less mode confusion and fewer mental model errors. Additionally, we still did not know which driving automation systems were most affected.

Therefore, non-parametric paired-sample sign tests were used to check whether symbol suites had a consistent effect on the occurrence of symbol confusion, mode confusion, and mental model errors. The results indicated significant differences where the *affording* suite was overall less associated with symbol confusion, $S(20) = 2$, $p < .001$, and with fewer mental model errors, $S(21) = 4$, $p = .007$, than the *standard* suite. No significant effect was observed for the mode confusion, $S(11) = 3$, $p = .227$. We can see in **Table 5.9** that the systems most concerned by symbol confusion with the *standard* suite were the ALKS, LCC, and LDP systems. The *affording* suite, on the other hand, was more concerned with drivers confusing the ACC symbol and the symbol displayed on the left-hand side of the steering wheel used to increase or decrease the headway/gap distance between vehicles (see **Figure 5.3**, page 151). Finally, we can also see that the systems associated with the mental model errors were similar between either suite. However, the *standard* suite was associated with more errors regarding the ALKS and ACC systems.

Table 5.9 Numbers of symbol confusion and mental model errors made per symbol suite and driving automation system.

Symbol Confusion	**ACC**	**LDP**	**LDP/LCC**	**LCC**	**LCC/ALKS**	**ALKS**
Standard	_	3	4	_	14	_
Affording	5	_	_	_	4	_
Mental Model Error						
Standard	28	_	_	_	3	24
Affording	16	_	_	_	2	14

To summarise and answer our first research question: yes, it seems that the *affording* symbols elicited more accurate mental models overall, which affected the frequency of mistakes made by drivers during both drives. The *standard* symbols were more associated with symbol confusion between the lane-keeping systems—namely, ALKS, LCC, and LDP—and with more mental model errors than the *affording* symbols.

B. RQ2: Transferability and intuitiveness of symbols

Our next research question was about whether both symbol suites were intuitive enough to be used without dedicated training, that is, only relying on previous experience with the other symbol suite. We already have two pieces of information to answer this interrogation: we saw that there was a trend for drivers to make fewer errors during the 2nd drive and that affording symbols were overall associated with fewer human errors during the 2nd drive. However, we did not know whether the latter effect refers to symbol confusion, mode confusion, and/or mental model errors. Consequently, we ran Poisson regressions for each of these human errors separately. The results indicated that the *standard* suite was more associated with symbol confusion during the 2nd drive ($\beta = -2.16$, Wald's $z = -2.87$, $p = .004$) as well as with more mental model errors ($\beta = -0.76$, Wald's $z = -2.19$, $p = .03$) than the *affording* symbols. Again, no significant difference was found between symbol suites for mode confusion ($\beta = -0.95$, Wald's $z = -1.59$, $p = .11$).

These results could indicate that the *affording* symbols are indeed more intuitive than the *standard* symbols as the former was less associated with symbol confusion and with fewer mental model errors, despite drivers having had previous experience with the same system but with different symbols. Nonetheless, another interpretation could be that a first experience with the *standard* symbols may have been more formative than a first experience with the *affording* symbols. This better formation would have then led drivers to make fewer human errors during the second drive despite potentially confusing *affording* symbols. However, we asked drivers to answer the following question after both drives ended: "Was it intuitive or confusing to use the new symbols on the 2nd drive?" To which, nine out of the 12 drivers who trained with the *standard* suite said that using the *affording* suite on the 2nd drive was intuitive. On the other hand, eight out of the 12 drivers who had used the *affording* suite during the 1st drive responded that using the *standard* suite was confusing. Therefore, the former interpretation seems more plausible.

In summary, the answer to our second research question is that the *standard* suite of symbols was overall more often associated with symbol confusion and with more mental model errors, but especially during the

2^{nd} drive due to the symbols being generally more perceived as confusing than their *affording* counterparts. Which symbols in particular or what made these symbols confusing remains partly unexplored, however.

C. RQ3: Drivers' attitudes towards symbols

In the last part of the experimental session, we asked drivers to indicate which symbol suite and individual symbols they would prefer to use in their car and explain their choice if possible. Overall, the *affording* suite as well as its symbols were preferred by drivers over their *standard* counterparts (**Table 5.10**). An exact binomial test indicated that the proportion of drivers who preferred the *affording* suite (.72) was significantly higher than it would have been had they chosen randomly, $p = .012$ (1-sided). This was also the case with the proportion of drivers who chose the *affording* LDP symbol (.79), $p = .001$ (1-sided). One-sample Chi-square goodness-of-fit tests indicated that drivers did not equally prefer the three options for the ACC, χ^2 (2, N = 29) = 13.73, $p = .001$, or for the LCC symbols, χ^2 (2, N = 24) = 27.25, $p < .001$. In other words, the superiority of the *affording* versions of those symbols is unlikely to be attributable to a random decision from drivers. Finally, as for the ALKS symbol, a statistical test did not point towards the same conclusion, χ^2 (2, N = 29) = 5.45, $p = .066$, as this symbol received a more mixed welcome from drivers.

The main reasons given by drivers for preferring the *standard* symbols were that they were already familiar with them and that they were visually simpler than the *affording* symbols. On the other hand, drivers who selected the *affording* symbols stated that these latter were more explanatory, more intuitive, and were "showing" the driver by telling stories both individually and as an ensemble. More precisely, the affordance symbology was noticed as drivers commented on the headway distance for the ACC symbol, the bouncing character of the LDP symbol, the hands on the steering wheel of the LCC symbol, and the 'MAX40' caption of the ALKS symbol. One driver suggested that these elements could remind them of the system's role and limits and potentially encourage an appropriate usage of the systems.

Table 5.10 Drivers' preference for the overall symbol suite or individual symbols.

	Standard	Affording	Either
Overall	8	21	0
			
ACC	4	19	6
			
LDP	6	23	0
			
LCC	3	20	1
			
ALKS	11	14	4

D. RQ4: Usability of SAE L3 systems

Finally, our last research question concerned the overall usability of vehicles equipped with driving automation systems ranging from L1 to L3, and whether using several levels of automation was intuitive or confusing for drivers. We thus asked drivers to say whether they found the five systems at their disposal were easy to use and whether they were useful. Eighteen (18) of the 25 drivers who were asked said that using the five systems was easy. Interestingly, a Bayesian multilevel Poisson regression confirmed that the drivers who thought that using the five systems was easy made fewer human errors than the other seven drivers ($\beta = -0.50$, 95% CI [−0.90, −0.07]). Furthermore, drivers' ATI scores (i.e., drivers' reported affinity with technologies) were not correlated to the number of human errors made during the experiment. In other words, anyone almost regardless of their abilities was prone to making errors while using a vehicle equipped with driving automation systems. From the comments received by the seven drivers who responded that it was not easy to use the five systems (**Table 5.11**), we perceive the difficulty for drivers to manage these many systems and controls, but also their willingness to receive instructions both while using the systems and before using them autonomously. We observed many mistakes and slips during the practice drives and experimental drives, such as drivers having trouble pressing the required number of times to activate a certain driving automation system or drivers pressing the wrong button. These errors could either be due to mental overload and/or inattention. Then, eight out of the 25 drivers thought that five systems were too many, 14 thought that five systems were just enough, and three drivers would have liked to have more systems. Again, by hearing drivers' comments (**Table 5.11**), one can realise how drivers were confused by the different lane-keeping systems, their respective functions, and conditions of use.

Table 5.11 Sample of drivers' comments about the easiness and usefulness of the five driving automation systems used during the driving simulation.

Question	Comments
Easiness	"**Difficult** to know which system to use in which situation. I'd need more time using them, […] the manual is **insufficient**. […] need driving lessons."
	"a lot to take in."
	"Activating/Deactivating was **confusing**. I would prefer several buttons and just one long press. […] Hard to look at the dashboard to check if a system is active."
	"The buttons and controls are **overwhelming**."
	"It was good to have **instructions**."
	"Overly **complicated**, it was difficult to know which systems do what and if they were off or on."
	"You wouldn't go out and use it straight away."
Usefulness	"**What**'s doing what? **Which** button to press? **Why** have LDP when LCC is on? […] **Too much** to learn […] not straightforward."
	"LCC and ALKS should switch automatically, that's just **stupid**."
	"I wouldn't use it with this **many systems**."
	"I liked the multiple functions, but I don't see the point of ALKS."
	"It could be **too much** for some people."
	"LPD is **useless** if you have LCC or ALKS."

To summarise, it was not only challenging from a psychological perspective for drivers to use a vehicle equipped with driving automation systems but also from a psychomotor perspective. Drivers needed to develop accurate mental models for five driving automation systems, whose functions sometimes overlapped, but also quickly map their controls on the steering wheel and coordinate their movements while remaining aware of the situation.

IV. General Discussion

1. Affording symbols: Are they more usable and do they elicit more accurate mental models?

We hypothesised that driving automation systems' graphical symbols integrating affordance-related representations—such as a system's actions or environmental signifiers—would improve the intuitiveness of said symbols and help drivers form and recall appropriate mental models. Compared to the *standard* or recommended symbols, the so-called '*affording'* symbols were indeed less associated with symbol confusion and mental model errors. More specifically, drivers made fewer mental model errors while using the affording ACC symbol and less confusion occurred between all three affording LKS symbols. We also replicated results from Perrier et al. (2019, 2021) where the ACC and LCC *affording* symbols were overall preferred to their *standard* alternatives used here. One driver also remarked how depicting hands on an LCC symbol could guide drivers towards a better understanding of how to appropriately use this system. This would be an important argument in favour of this symbol as overreliance has already contributed to fatalities in cases where drivers were reportedly misusing Tesla's autopilot by driving handless (e.g., AutoBlog, 2021; Consumer Reports, 2017, 2018).

Landry et al. (2022) have shown that the ability of drivers to understand a Volvo car's HMI while using ACC varied from novice to expert users. Equally, we had previously mentioned (page 140) that drivers' ability to deduct a system's limitations was generally poor (Aziz et al., 2013). Therefore, although standardisation and familiarity are important to prevent drivers from having to learn how to use a new vehicle, intuitiveness is at least equally important to tackle those cases where a naïve driver will get access to a vehicle equipped with driving automation systems without prior training such as in rental cars. Here, we showed that affording symbols were better understood by drivers and consequently led them to commit fewer errors than when using other symbols.

2. The case of ALKS' interface: Is a symbol enough?

Our results also suggest that in some cases, a graphical symbol might not be sufficient to communicate a car's current level of automation. Well-designed symbols allow the fast and effortless communication of complex concepts, but there could be a limit to how complex a concept can be to be symbolised graphically. Some drivers have commented on the relative visual complexity of the *affording* symbols, and we observed how drivers could be confused by the differences between all three LKSs presently tested and their respective usefulness among this very triad. There is a strong paradigm shift from L2 to L3 for drivers in terms of responsibility and mental mindset. This paradigm transition automation levels could therefore also be accompanied by a change in HMI design more pronounced than a mere symbol on the instrument panel.

Firstly, this shift can be visual: with a new colour code already established by BMW (Naujoks et al., 2019) and Mercedes-Benz with their new Drive Pilot: up to L2, the interface uses a green palette for its activated driving automation systems' symbols and switches to a blue/turquoise palette from L3 and above (**Figure 5.5**). Beyond colour, and to adapt to the fact that drivers do not have to remain attentive to the road scene, lights can be placed on or around the steering wheel as peripheral visual signals. This is already used by Mercedes-Benz's Drive Pilot (**Figure 5.5**) and Cadillac's Super Cruise (Cadillac, 2020), but has also been explored in research for a certain amount of time now (e.g., Borojeni et al., 2016; Diederichs et al., 2022)—although, not necessarily to indicate automation levels. Then, ambient lights within the car have been explored with different purposes in mind, which could also mark a radical change from SAE L1 and L2 (e.g., Kunze et al., 2019; Löcken et al., 2016; Louw et al., 2021; van Huysduynen et al., 2017).

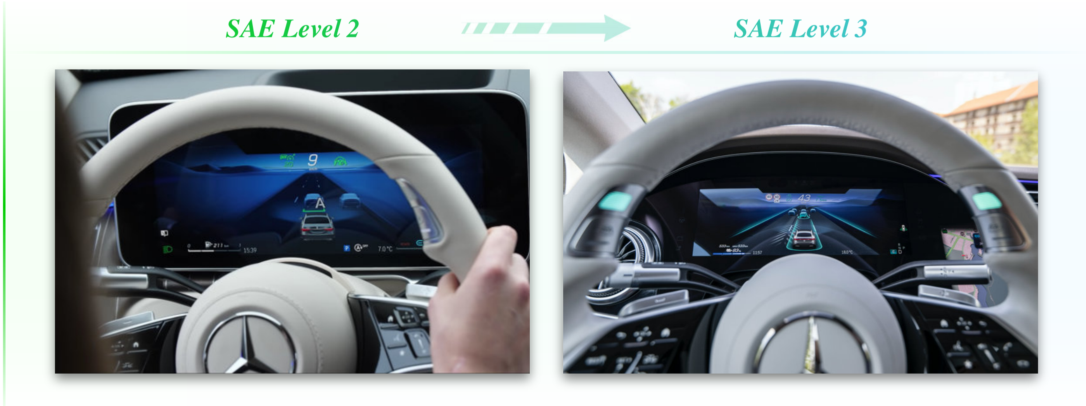


Figure 5.5 Mercedes-Benz' Drive Pilot HMI. Up to SAE L2, green is used to colour driving automation systems' symbols. From SAE L3, blue/turquoise replaces green to indicate the change of drivers' roles. (video source: https://youtu.be/1gjweWq8qAc)

Secondly, apart from a purely visual aspect, the shift from assisted driving (L1 and L2) to automated driving (L3 and above) could make use of the car's controls. For instance, Muslim et al. (2022) had drivers use the gear shift to engage L3, going from D (Drive) to D3. This has the advantage of being different enough from activating ACC or LCC by pressing a button or pulling a lever. However, sufficient time should be allocated to drivers when falling back from D3 to D if this would imply going back to manual drive as driving performances can worsen after a transition of control (e.g., Pampel et al., 2019; Wu et al., 2022).

Research comparing designs that combine all these elements is still needed to help standardise our vehicles in the near future when various interfaces are already proposed or being announced. Apple CarPlay, for instance, should allow drivers in the future to replace their car's original instrument panel with designs varying in levels of visual clutter and complexity (**Figure 5.6**). We had previously observed that drivers could prefer different HMI designs for their vehicles (Perrier et al., 2022), one driver even stated that they could switch to a simpler interface once they would have learnt how to use the system. Similarly, one participant in the present study postulated that they could use the *standard* symbols after learning how to use the driving automation systems with the *affording* symbols. Although the latter example would go against the purpose of standardisation, these comments illustrate how some drivers could imagine learning by first making use of visual aids before switching towards more minimalistic user interfaces. From a user experience (UX) perspective, this also raises the question of whether automakers should personalise the whole driving experience by logging the driver before each drive, allowing them to propose not only a personalised interface, but also personalised access to each driving automation system given that the driver would have had completed a pre-required training, tutorial, or entered a valid driving license number.

Figure 5.6 Samples of Apple CarPlay announced interface styles. Source: Apple WWDC 2022 (developer.apple.com/videos/play/wwdc2022/101/).

3. Several levels of automation: Is it confusing or intuitive to use?

Indeed, drivers variously complained about the complexity of the simulated vehicle used in our study. Previous experience with similar systems could have helped drivers understand the vehicle better, but drivers' reported affinity with technology did not predict who would struggle or not. Some drivers felt the need to receive training to feel safe using such vehicles by themselves, the handbook being insufficient according to one driver. Solutions have been proposed, such as in-car tutorials (e.g., Boelhouwer, van den Beukel, van der Voort, Verwey, et al., 2020; Forster et al., 2019) or adapted driving licenses (European Commission, 2017)—France has included questions about ACC in its theory exam, for instance. In our study, audio-visual assistance via notifications and alerts was appreciated, but drivers were sometimes confused by the alert stating that the car had "obstructed sensors", drivers not linking this to the fog. Therefore, automakers should also make sure that any message is unambiguous for most people.

User interfaces and systems should have a “high-level of commonality of design”, as proposed by the UNECE (2022), in order to prevent misuse and errors of operation. From our results, this could mean reducing the number of systems and interactions between the driver and their vehicle. Indeed, several drivers interrogated the respective usefulness of the three LKS, and why the decision of switching between LCC and ALKS was eventually up to them. Most driving automation systems on the market today were arguably commercialised because the technology became available at the time and represented an advantage over other automakers (Dutch Safety Board, 2019, p. 62). Today, however, we can question the usefulness of CC when ACC is available, why dynamic cruise control—adapting the vehicle’s speed in curves—is not systematically integrated into ACC, or why drivers would have to deal with three or four levels of lane support (i.e., LDW, LDP, LCC, and ALKS). Indeed, similarly to another study where authors observed drivers confusing CC and ACC (Strand et al., 2011), three of our drivers crashed into other vehicles while using CC because they thought they were using ACC. Equally, two drivers crashed because LDP would not let them change lanes without using their indicators.

Finally, using an L3 ADS-ready vehicle was rather confusing for most drivers, because of the complexity of the mental models to develop and the interactive aspect of the vehicle. The number of buttons, control patterns (e.g., single/double presses), and the number of interactions should be reduced by making sure that environmental conditions are satisficing before allowing drivers to use a particular system, for instance. Using geolocation, weather data, cameras or other sensors for this purpose could prevent inadvertent behaviours, unexplained deactivations, and eventually “automation surprise”.

4. Limitations

Firstly, without time constraints due to a funding deadline and the COVID-19 pandemic, more respondents could have been involved in the survey and a participatory design workshop would have been considered to invite drivers and ideate symbols for LDP and ALKS. We do not believe, however, that this was detrimental to the results and interpretations of the main study. Indeed, the LDP symbol chosen for the *affording* suite received an 80% appropriateness score and was rated much higher than the other symbols, including the *standard* one (54%; see **Table 5.1**, page 146). As for the ALKS symbol, the *affording* symbol was consistently rated higher, with or without the caption, in the survey and was very much in line with the ideas that drivers generated in a previous design workshop for LCC (Perrier et al., 2019).

Secondly, one could argue that we did not interrogate and ensure that drivers remembered everything after reading the manual during the main study. This was a deliberate decision to try and simulate the experience that drivers could get when acquiring a vehicle equipped with driving automation systems; a situation which is arguably still not the worst that could happen to a driver, them not systematically reading their car manual (Oviedo-Trespalacios et al., 2021). It was interesting to see how intuitive the system would be for drivers who had never used anything similar, and who would not have been introduced to their car by their dealer (see Boelhouwer, van den Beukel, van der Voort, Hottentot, et al., 2020).

Fourthly, questions were added to the semi-direct interviews after the first day of experimental sessions, which somewhat reduced the number of respondents for these questions—namely, the easiness, usefulness, intuitiveness, and preference for the LCC symbol. Drivers, however, tended to comment on all questions in advance while giving their overall impressions of the study, which is also why these questions were added. Therefore, the impact on the content gathered during interviews was only slightly affected, if affected at all.

5. Future directions

How internal HMIs should be designed to differ between SAE L2 and L3 is a question that urgently needs an answer, both in terms of physical interaction (i.e., controls) and in terms of audio-visual interaction for monitoring and transitioning purposes. External and internal HMI designs should inform regulatory organisations to establish standards that will protect the drivers of L3 cars themselves, from misusing their vehicles or making errors, as well as other road users.

Finally, research should be conducted to assess how drivers tend to organise driving automation systems hierarchically and establish intuitive mappings of these systems to the physical controls of the vehicle. Studies showed how the organisation of automation levels does not fit drivers' mental models (Homans et al., 2020; Zacherl et al., 2020), and the challenge is to know whether these levels should be abandoned entirely, reformed, or kept for theoretical issues only. Engineers and designers should be informed on how to conceptualise driving-assistance systems and how to give access to these systems to drivers via the controls. Manufacturers branding each of their driving automation systems with an original appellation may also get in the way of vehicles having a harmonious design and should be regulated promptly, at least for the sake of preventing driver confusion (see AAA et al., 2020).

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Appendices

Symbols compared in the survey

Appendix 5.1 Index of symbols tested for lane departure prevention (LDP) and automated lane-keeping system (ALKS) during the online survey. The symbols are organised by symbols ideated by the authors and symbols designed after existing standards or regulations.

Systems' definitions

Appendix 5.2 Descriptions of the four systems given to respondents during the appropriateness and suitableness tests.

System Name	System Description
Assistance A *adaptive cruise control (ACC)*	Accelerates and decelerates your vehicle to maintain a maximum speed and safety distance between you and the vehicle in front.
Assistance B lane departure prevention (LDP)	Detects the markings of the lane in which you are driving and can momentarily apply steering to correct your trajectory and prevent you from leaving your lane unintentionally.
Assistance C *lane centring control (LCC)*	Steers the vehicle on its own but you must remain attentive to the driving scene and intervene if necessary.
Assistance D *automated lane-keeping system (ALKS)*	Controls your vehicle's speed and trajectory just like Assistance A and C combined. You can focus on other non-driving-related activities but need to remain physically available to intervene at your vehicle's request. At the moment, drivers may only use this latter system under 40 mph on roads where there is a physical separation between traffics such as motorways.

Human factor codes' definitions

Appendix 5.3 'Human Factor' codes used to analyse the video recordings and code the qualitative data.

Human Factor	Definition
Unfamiliarity	The failure to interpret a symbol or activate a given mental model due to a lack of knowledge about the corresponding system mode.
Confusion: Symbol	The activation of an erroneous mental model due to the misinterpretation of a symbol.
Confusion: Mode	The maintenance of an erroneous mental model of the current system mode due to a misinterpretation of the environment or lack of mode awareness.
Inaccurate Mental Model	The maintenance of an erroneous mental model of the system mode due to a lack of knowledge.
Automation Surprise: Confusion	An action executed by an automated system that is unexpected by the driver and leads to confusion.
Automation Surprise: Realisation	An action executed by an automated system that is unexpected by the driver but is correctly interpreted.
Inattention	The failure to maintain an adequate level of attention towards a driving-related activity.
Mental Overload	The maintenance of a level of cognitive demand that is too high for the driver.
Trust: Overreliance	An inappropriately high level of trust in automation and its ability to safely carry out its function.
Trust: Mistrust	The belief that automation can fail to execute its function reliably.
Satisfaction/Dissatisfaction	A positive/negative attitude towards interaction with or attribute of the automated system.

Chapter VI
General Discussion

I. Grand Summary of the Research

1. Research context & objectives

This research was co-funded by **The University of Leeds**, the **Engineering and Physical Sciences Research Council** (EPSRC), and **Bosch UK, Ltd**.

The principal motives for conducting this PhD were, firstly, to help develop solutions for practical design problems that were observed in the automotive market, and secondly, to expand our scientific knowledge on the topic of graphical symbols and HMIs for automated driving vehicles while suggesting avenues for further research. Indeed, design inconsistencies in the way vehicles equipped with driving automation features inform drivers about a particular system's state, capabilities, or limitations, could potentially provoke confusion among drivers, notably if said drivers were to use several vehicles on a daily or occasional basis. Additionally, some of the designs could be less usable than others, and too little research has been conducted showing how seemingly small HMI design choices could affect the usability of vehicles equipped with driving automation features.

The aim throughout this project, therefore, was twofold: ① to demonstrate whether symbol confusion was an actual risk for drivers and whether the different designs for symbols and interfaces could have measurable consequences on a vehicle's usability, and then ② to determine which methodological approach could help design symbols and interface elements that would prevent or mitigate these putative consequences. The results obtained after conducting the four studies presented in this thesis allow us to answer positively to the first issue while suggesting answers to the second one.

2. Answering the research questions

A. Firstly: Is there a problem?

The results presented throughout Chapters 2 to 5 of this thesis confirm that, *yes*, using certain graphical symbols and visual HMI elements over other ones will have repercussions on a vehicle's usability.

Chapter 2 exposes the first study conducted for this project, whose purpose was to explore drivers' mental models of the two main systems responsible for partially automated driving (L2): ACC plus LCC. Drivers took part in a participatory design workshop and were given the descriptions of four different systems, namely, CC, ACC, LDP, and LCC. They then sketched different symbols for ACC and LCC, selected one of their sketches for each system, and explained their concept to the rest of the group. The participants then commented collectively on other symbols that were either found on the market or designed for the workshop. Interestingly, six out of the seven ACC symbols found on the market included at least one element that could be misinterpreted by at least one of the seven drivers present at the workshop, be it radar waves read as the Wi-Fi symbol[††††] or a speedometer seen as a steering wheel. In parallel, the lines and hands' designs in the LCC symbols could be interpreted differently, with continuous lines seen as indicative of a system that would never cross the lane's lines, or the presence of hands meaning a system that would be assisting rather than fully automating steering. The results from this workshop, although they did not demonstrate that confusion could occur between the symbols of different driving automation systems, at least showed that drivers could face difficulties in their first uses of a vehicle equipped with ACC and LCC depending on the design of the symbols.

In Chapter 3, however, the results from an online survey—whose purpose was to have drivers guess the meaning of an ACC and LCC symbol and then match seven systems to their symbol—showed that confusion could happen between LDP and LCC, especially if the LCC symbol depicted

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[††††] This was not detailed in Chapter 2, because of the word limit imposed by the original publishing format, as such, some information had to be withdrawn.

hands holding a steering wheel. This result was congruent with what had been suggested by drivers during the workshop and with the notion that symbols in a set should be as close as possible to their own concept but as far semantically as possible from other symbols (Silvennoinen et al., 2017). Moreover, the ISO symbol for ACC was the most confused with the conventional CC system due to the lack of ecological signifiers such as the headway (Gibson & Crooks, 1938).

Ultimately, one of the objectives of the final study reported in Chapter 5 was to demonstrate that symbol confusion between systems could occur while drivers were driving and to observe the consequences. Drivers were invited to participate in a driving simulator study and use five driving automation systems: CC, ACC, LDP, LCC, and ALKS. Drivers, consequently, had free access to the levels 0, 1, 2, and 3 of driving automation. Drivers sometimes confused the symbols between LDP (L0) and LCC (L2), between LCC and ALKS (L3), or between a particular ACC symbol and another symbol used for setting the distance between one's own vehicle and the preceding one. From these confusions originated misuses and use errors, including drivers taking their hands off the steering wheel while using LCC (a hands-on system in this study) or drivers being distracted and confused as to why ACC would not activate when they pressed the aforementioned distance setting button. This study showed that the symbols of driving automation systems could participate in the formation and recall of mental models, congruently to what Jung and Myung (2006) reported, and that ISO symbols for ADAS were not necessarily preferred by drivers, which had already been demonstrated for road signs and other car symbols (Payre & Diels, 2019; Sayer & Green, 1988).

Additionally, the first simulator study, related in Chapter 4, was conducted to have drivers drive with ACC and use three HMIs whose graphical elements could change: the symbol for the system, the speedometer, and the visual aid for setting the headway distance. The results showed that task completion time and total glance time measures could differ between the different HMI elements, these differences being generally consistent with what psychology research on visual attention could predict. Nonetheless, although some visual elements were objectively preferable to others, some drivers still preferred to use certain options that were objectively deemed less efficient. This showed that differences could be observed not only in terms of efficiency but also in terms of pleasantness. Additionally, one of the objectives while conducting this study was to have drivers use a custom-made speedometer that was supposed to intuitively inform drivers about some of the capabilities of their vehicles: whether the minimum speed that the driver could set was different from the minimum speed at which the car could drive in slow traffic. This design, however, received mixed results as it was not intuitive enough for most drivers to understand the capabilities of the system, while, on the other hand, several drivers retrospectively commented that it was clear once these capabilities were explained. Whether the speedometer's design was not intuitive enough or whether this particularity of the ACC system to have different speed ranges is not understood, remain unanswered.

To summarise, symbol and HMI designs ***can*** have observable effects on a vehicle's usability, by provoking confusion or affecting the attentional demand of a task. The question, therefore, is which approach could inform the better design of graphical symbols and HMIs to prevent these nefarious effects?

B. Secondly: Is there a solution?

From the results exposed in Chapter 2, it first appeared that a driver-centric approach to the design of symbols was preferred to that of a system-centric approach. Drivers ultimately opted for symbols that would be more relatable to them and close to their driving experience rather than symbols that would represent how the system was engineered, although they might have sketched symbols revolving around that idea at first. The way the systems operate was eventually not the most meaningful part of their mental models, whereas the context and their perception of the driving scene appeared more essential. As such, drivers would prefer an ACC symbol representing the headway distance separating their car from the preceding one as seen from the driver's seat rather than a symbol depicting a car and radar waves, or rather than a symbol depicting a side view of two cars and the distance separating them. For LCC, the lane markings and the interaction between their hands and the steering wheel were meaningful signs, whereas depicting the use of cameras for detecting the lane markings was not, or depicting only a steering wheel without any more context. From this first study, affordances arose as an important concept for designing symbols that would be intuitive for naïve drivers.

The results from the online survey presented in Chapter 3 were pointing towards the same direction, as the ACC symbol representing the headway distance seen from the driver's perspective was the most recognised and least confused, while design changes to the lines and hands in the LCC symbol could result in the symbol being less recognised or even confused with LDP. In this latter case, the lines' design was interpreted in accordance with real-life signifiers: dashed lines generally authorise lane changes whereas continuous lines normally do not, somewhat consistently with how Gibson and Crooks (1938) first imagined the driving task from an ecological perception approach. But furthermore, the confusion between LDP and LCC was hypothetically due to the design of the standard LKS symbol not representing the actions and signifiers well enough. A new symbol was therefore researched and tested in the last study of this project.

The results, presented in Chapter 5, agreed that symbols relying on the concept of affordances were better for drivers: the ACC, LDP, and LCC symbols in the affording suite were not only preferred but also less associated with mental model errors and confusions during the drives. The LDP and LCC affording symbols were less confused, and the LCC symbol was less confused with the ALKS symbol, which showed that the representation of use affordances (Pucillo & Cascini, 2014) via the depiction of hands or not could help differentiate the LCC and ALKS symbols and promote appropriate use. The final design for ALKS, however, was not satisfactory enough as drivers' preference for this symbol was not as clear as for the other systems. Moreover, the design may not be distinct enough from the LCC symbol, partly due to both systems being very similar and the requirement of keeping symbols simple enough. Although drivers appreciated the mention of "40 MAX" in the affording ALKS symbol to reflect the system's ODD, these L3 systems are now authorised to be used at up to 130 km/h, that is, ≈80 mph (UNECE, 2022), making the use of such a caption obsolete. Designing symbols for future automated driving features may become more and more challenging, as for drivers, the practical differences between L3 and

L4 may be less clear than between L1 and L2, for instance. This research suggests the limitations of symbology to convey differences between automation features and changing driver roles. As discussed in Chapter 5, the automation levels above L2 should maybe be communicated via more than just a symbol change, and rather via an ensemble of visual and auditory cues and changes on the HMI. If affordances have proven to be a promising orientation for symbols' design, this concept could be extended to the rest of the HMI, as illustrated in Chapter 1 with the example of the rotating seat (Jochum et al., 2022) and telescopic steering wheel (e.g., Audi’s Skysphere concept car).

The attempt at designing an informative, intuitive, and efficient speedometer was mostly unsuccessful because drivers did not perceive the affordances; because they were unaware that they existed and because the signifiers were not the right ones to communicate that they existed to naïve drivers. Either this speedometer should be redesigned or drivers should be informed beforehand about the capabilities of the ACC system (which would defy the purpose of having an intuitive design...). Still, this study has the merit of showing that designing with an ‘*affording approach*’ in mind would be insufficient for a designer and should be accompanied by user testing.

C. *Other results and contributions*

Although the main contributions of this work were to show that symbol and system confusion could be an issue, that HMI design decisions could affect the efficiency aspect of a vehicle’s usability, and that designing around the concept of affordances could help solve these issues, other results were observed that contributed to expanding our knowledge in terms of design and human factors of automated driving.

Firstly, drivers having only some familiarity with driving automation systems would help the development of intuitive symbols and HMIs. In the online survey of Chapter 3, it appeared that drivers who had at least some knowledge about driving assistance or driving automation features were better at recognising symbols than those without any knowledge. This shows the importance of at least educating drivers, especially new drivers, about these features as owning and/or having used these features before only had minor to no benefits on symbol recognition.

Vehicles equipped with automated driving features are selling all around the world, regardless of the rigidity of drivers' education in the selling country. Educating drivers about these systems is, regrettably, much easier to do in a country that requires drivers to pass a theory exam than in a country that simply sells their driving licenses for less than £50/50€ like Mexico[‡‡‡‡]. The European countries, the USA, Canada, Australia, China, Russia, and more, should therefore work towards integrating the topic of automated driving features into the theory test of their driving license requirements. For those drivers that already passed their driving test, it is in the hands of manufacturers to integrate training programs in their vehicles, of car dealerships/rentals to educate their customers when appropriate, and of governments to occasionally lead informational campaigns via TV channels and social media, for instance.

Finally, a successful combination of UCD and participatory design was achieved for this project, whereas at least one other PhD project could not observe the benefits of using participatory design for designing truck HMIs (François et al., 2021). Speculatively, the reason for this difference could be that participatory design here was only used during the early stages of the design process and for something less holistic than designing a whole instrument panel. As mentioned in Chapter 1 and Chapter 3, asking users to design something for themselves comes with limitations as users are not designers and will generally be ignorant regarding good and bad design practices (Bailey, 2005; Marti & Bannon, 2009).

II. Précis of the Research

Succinctly, during this PhD, a combination of UCD and participatory design was used and helped us understand more about drivers' mental models of driving automation systems, it also helped assemble a set of affording symbols that were overall more usable than the standard or recommended symbols, and finally helped highlight that the design of

[‡‡‡‡] See also Zuto.com (2020) for a comparison between countries.

some HMI elements for the ACC system was more efficient than other ones.

Indeed, affordances appeared to be an important concept for building and recalling drivers' mental models of automated driving features. Designing symbols around these affordances eventually improved the intuitiveness, pleasantness, and effectiveness of the vehicle. However, using symbols for another purpose than communicating a system's state can be less efficient than other alternatives in the case of the ACC symbol, which was used for setting the headway distance from preceding road users.

Finally, familiarity is essential for perceiving affordances and understanding an HMI in all its aspects; be it symbols or other HMI elements. Drivers acquainted with the systems or self-reportedly "comfortable with technology" could still be challenged and make errors while using the different systems. Therefore, educating drivers about automated driving features is also important for improving the inherent intuitiveness of symbols and HMIs.

III. Critical Reflection on the Research

This research, although it was attempted to be conducted rigorously, still has limitations of whom the reader should be aware to interpret the outcome fairly. Firstly, the designs used throughout this project did not go through many iterative steps as might occur in a design firm for instance, and no professional designers or illustrators were involved in this project. Furthermore, the designs relied heavily on my interpretations of drivers' input based on what I knew at the time and were my representations of these interpretations. Although, this would also apply to any designer or illustrator. In addition, there were limitations due to the methods employed in the research.

1. Qualitative methodology

Qualitative research, in contrast to quantitative, is less interested in modelling the world by numbers and more in the understanding of the dimensionalities of an object and its relations with other objects;

philosophical interpretation is part of the research and its research methods are more flexible than quantitative ones (Mason, 2017). One disadvantage of observational data, however, is that the analysis can be very time-consuming. Therefore, it can be difficult to find someone willing to dedicate their time going through hours of data coding and capable of sustaining the motivation to produce reliable data throughout the days. This issue applies to the research reported in Chapters 3 and 5, and consequently, only I coded the data, and therefore, could have been biased during data coding.

However, involving another coder could have involved other biases, particularly for the research reported in Chapter 5: I could not have expected an external coder to establish the exact same list of inductive and deductive codes, especially if they were not expert of the field, and therefore, I would have been constrained to provide them with my own list. Consequently, I should have trained the coder to make sure that they understood each code, were able to differentiate them from each other, and were able to code the data accordingly, which in addition to being time and effort consuming (e.g., Berends & Johnston, 2005) could in itself have biased the results. I myself needed to look back at the codebook many times; a step that could be overlooked by an unmotivated coder who would start applying the code definitions differently over time, another bias known as 'observer drift' (Harris & Lahey, 1982). In conclusion, biases can be encountered in either cases, and what is theoretically expected from researcher may not be easily achieved in practice, especially for early career researchers, unfortunately (Campbell et al., 2013)

A second concern, although it is not limited to qualitative research, is that the observer should be impartial towards the research so as to not bias the way they could interact with participants, but especially more during qualitative research as this bias can occur after data collection and during data coding or analysis (Queirós et al., 2017). As such, this bias could have occurred in the research reported in Chapters 2, 4, and 5, mostly. Conscious of this problem, I have of course attempted to remain cautious and impartial throughout the conduction of these studies.

Lastly, it can be difficult to have participants verbalise their thoughts and opinions, which can result in the data collected not being representative of the target population. Mostly, the research reported in Chapters 2, 4, and 5 is affected by this issue. One way of somewhat counteracting this in Chapter 5 was to include concurrent probing as some drivers progressively stopped commenting on their driving or were naturally introverted.

2. Driving simulator

Compared to experimental studies conducted with real vehicles, driving simulators offer several advantages with respect to the controllability and reproducibility of the driving conditions; the possibility of setting up situations that would otherwise be dangerous; the greater freedom for communicating instructions and feedback; a facilitated data collection; and a lower cost of operation (Carsten & Jamson, 2011; de Winter et al., 2012). Nonetheless, there is ongoing discussion as towards the validity of research outcome obtained through simulation. One could argue that simulations are an attempt to 'immerse' participants in an experience and make them forget that this is not the analogous real-world situation they might be already familiar with, all while convincing them that all the rules that apply to the said situation also apply in the simulated environment (Carsten & Jamson, 2011).

Presence, or 'psychological immersion,' can be defined as a state of absorption and engagement, where an individual's attention, thoughts, and goals are all directed towards a single experience (Agrawal et al., 2020; Lombard et al., 2009). On the other hand, *immersion* refers to the objective property of a system or technology to deliver sensorial modalities all while preserving their fidelity in relation to their real-world counterparts (Agrawal et al., 2020; Slater, 2003). Depending on which elements compose a simulator one will categorise this latter as being high-level, medium-level, or low-level fidelity, like the one used for this thesis. Interestingly, these two concepts can be compared to the notion of *fidelity of simulation* (McCormick, 1964; Mudd, 1968), sometimes also labelled *validity* (Blaauw, 1982). Indeed, fidelity can be decomposed into *psychological fidelity* and *physical fidelity*, wherein psychological fidelity refers to how the behaviour observed in the simulation approximates that of the real experience of driving, whereas physical fidelity refers to the correspondence between the physical components of the simulator to those of a real vehicle.

Accordingly, one may discern how immersion, as defined previously, can be approached to the physical fidelity of a driving simulator and how immersion may serve presence and the psychological fidelity of a simulation. One can reasonably presume that the higher the physical fidelity of a simulator the more it will facilitate the reproduction of a certain behaviour, thus, the more an individual will be immersed and the more their behavioural responses will bear some validity. This capacity of a simulator to reproduce a behaviour as it is observed outside of the simulator (or psychological fidelity) can also been decomposed into two qualities: *relative validity* and *absolute validity* (Blaauw, 1982). If one compared a driver's behaviour or performances inside of a simulator to the same driver's performances in a naturalistic environment and found that these performances were of similar order and direction, one could say that the simulator has a relative validity. Furthermore, if a driver's performances were to be numerically equal in both environments, then the simulator could be qualified as having absolute validity.

A review of 44 studies, comparing performances obtained during simulated driving to on-road driving, reports that about half of the total 52 driving simulators compared either achieved absolute and/or relative validity (Wynne et al., 2019). The authors further report that some low-fidelity simulators did qualify for validity while some high-fidelity simulators did not, indicating that the answer to our question is not simple. For instance, the fidelity of the visual simulation may not affect driving performances (Reed & Green, 1999) whereas the presence of a physical vehicular cabin can help reduce lane deviation (Mecheri & Lobjois, 2018); the hypothesis of the authors was that the cabin allowed for a better estimation of the vehicle's position within the lane compared to single-screen monitors like they can be found in most low-fidelity simulators. Many studies exist comparing fixed-based to motion-based simulators and real-world driving that have found similar driving performances, visual attention, or physiological measures (e.g., Engström et al., 2005; McWilliams et al., 2019; Reimer & Mehler, 2011; Robbins et al., 2019;

Santos et al., 2005; Spyridakos et al., 2020). A study by Merriman et al. (2021) also showed that drivers' perception of risks was only marginally different between a low-fidelity simulator, a medium-fidelity simulator, and on-road driving, this perception of risk supporting the idea that participants could behave authentically during driving simulator studies. These authors concluded that their results supported the use of driving simulators for studying driver distraction.

A researcher's decision as to which level of fidelity they should use for their driving simulator study may very much depend on external factors such as rental cost, availability of simulators, number of operators needed for each sessions but also during development, and probably more. The literature suggests that the benefits of high-level fidelity driving simulators is not as clear as one could think; moreover, all simulators come with their disadvantages, such as motion sickness for motion-based simulators, for instance. In the studies reported in Chapters 4 and 5, the low fidelity of the steering input sometimes engendered stressful situations for participants, especially for a handful of them. A few participants, surprised by the sensitivity of the lateral control when they first tried the simulator, overcompensated their left and right steers when trying to correct their trajectory, which resulted in them getting panicked and zigzagging on the road. Especially one elder driver struggled and needed more time to adjust their steering. However, drivers were more comfortable after the training drives, which were not included in the analysis. In the event of anything of the sort happening during the experimental drives, the notes taken during the sessions (in Chapter 4) or the video recordings (in Chapter 5) were used to eventually remove these trials from the final analyses.

Finally, the HMIs as well as some parts of the custom software for the driving simulator were developed specifically for these studies with limited time and resources in between lockdowns during the pandemic of COVID-19. Although their final qualities were good, additional time would have allowed more tweaking and improvements on minor bugs and overall behaviours. For instance, in Chapter 5, pressing the accelerator pedal deactivated the ACC system, which therefore also deactivated LCC or ALKS if the systems were active. Or again, the HMI initially had a bug where if LDP was deactivated while the LDW alert was sounding, the alert would loop until the system was reactivated or the HMI restarted. This bug as well as other ones were fixed after the first sessions.

3. Eye-tracking setup

Eye gazes can be estimated using an eye-tracking device that detects the pupil—the darkest region of the eye—and correlates its shape and distance from the brightest spot on the cornea—or corneal reflection—which should originate from the source of infra-red light sent by the eye-tracker (Valtakari et al., 2021). The device can either be mounted on plastic frames and be worn like glasses (*head-free* setup) or fixed on a platform independently from the subject (*head-boxed* setup). Additionally, the person can rest their chin on a chin-rest in order to have their eyes affixed in space (*head-restricted* setup). The driving simulator study conducted for this project made use of a head-free setup, which presents several inconveniences: the precision is poorer compared to the other setups, going from 0.5 angular degrees of precision for a head-free setup, down to 0.01—0.03° for a head-restricted setup, which is therefore about 15 to 50 times more precise. Then, the accuracy is also poorer for head-free setups, going from errors of 1—3° to as low as 0.5° for head-restricted setups. This was a limit for the analysis as it was infeasible to determine where exactly participants were looking on the HMI and have a deeper analysis of the data. Finally, the glasses holding the eye-tracker could move during the session, simply because participants talked, scratched their faces, or adjusted their face coverings in our case during the COVID-19 pandemic. In this regard, having relatively short drives helped mitigate this issue.

IV. Directions for Future Research

This work, in addition to providing answers to some questions, also opened new perspectives for more research on the topic of automated driving features and their HMIs. Firstly, defining what an affording HMI could be in relation to the current and future systems, notably ACC, LCC, and ALKS. In Chapter 4, an affording speedometer for ACC was investigated; however, the results regarding its usability were mixed.

Designing a speedometer for ACC using UCD or participatory design methods and comparing it to manufacturers' designs could be interesting. Additionally, designing an HMI for L2 and/or L3 using the same approach could help drivers not only differentiate more between these driving modes but also maintain them in the right mindset. Indeed, research has shown that about 45% of drivers used an L2 system with both hands off the steering wheel, 30% engaged in a non-driving related task with both hands, while a bit less than 20% had at least one hand busy interacting with an object in the vehicle (Reimer et al., 2016). These numbers were accentuated during L3, but are more concerning considering that drivers should be monitoring and remain ready to take over the driving task during L2. Having an HMI that promotes engagement in supervising the system and environment during L2 is therefore crucial for keeping our vehicles safe to use. Additionally, designing a better ALKS symbol than the one used for the research in Chapter 5 would be necessary. Finally, more work should be done to determine the limitations and opportunities for using participatory design during the conception of HMIs for vehicles equipped with driving automation features.

Future research, however, could be challenged by new legislations, regulations, and market changes made within the next decade. This very research has been a perfect example of this as, since it started, ALKS has been regulated, commercialised, and then updated so that the maximum use speed could exceed 40 mph | 60 km/h (UNECE, 2020, 2022). The Department for Transport of the United Kingdom also investigates whether the use of hands-off L2 systems is safe compared to hands-on systems and whether they should be authorised on British roads. Knowing that such hands-off L2 systems are authorised for use on many North American roads, this poses a challenge for both researchers and OEMs, but also raises the question of whether global regulatory action should be taken in order to ease the research and design processes around these systems. Moreover, which non-driving related tasks (NDRT) should be allowed during L3 driving is also being discussed and should be regulated in the future, which will have implications for the design of HMIs and symbols. New messages and symbols could become necessary to educate drivers about their responsibilities, provide feedback on their behaviour during L3 driving, and maybe in other cases. Whether these putative symbols should also be regulated would become a new issue.

Additionally, whether driving automation systems' symbols will remain an important part of drivers' experience in the future is also a concern. Current L1 and L2 systems may at some point become irrelevant in passenger vehicles capable of L4 or L5, but also in robotaxis, such as Waymo or Cruise in the USA, or driverless buses, such as those tested by Navly or the RATP in France. However, there are reasons to believe that symbols for L1 to L3 systems will remain in passenger vehicles and that their design remains an important issue for usability. Firstly, the L4 and L5 systems may not become available in passenger vehicles before a long time and their use will likely remain limited to relatively small portions of our total infrastructure. The availability of L4 and L5 systems, therefore, does not exclude the use of L1 to L3 systems in other scenarios where using L4 and L5 systems is impossible. Secondly, there is a trend among OEMs to abandon physical buttons and privilege flat touch-sensitive surfaces, which increase the visual demand from the driver due to the lack of tactile sensations (Cockburn et al., 2018; Ng et al., 2017), and reinforces the need for clear graphical symbols. Thirdly, modern vehicles sometimes offer different instrument panel layouts and can be subject to regular minor or major UI updates, if the vehicle is connected to the internet. Different instrument panel layouts can mean that the location of the driving automation feature symbols may vary, and therefore that drivers cannot rely as much on their visual-spatial memory to identify which system is active or not compared to if symbols' locations were invariable. In such case, the risk of symbol confusion could increase.

In the future, systems at all levels of automation may still evolve in their capabilities and limitations, as well as their names since no regulation enforces commonality yet (but see AAA et al., 2020). Thus, symbols can be a common anchor for similar categories of systems to quickly inform drivers about something that they have not been educated about, be it during their driver formation, by their reseller, or their car owner manual.

V. Recommendations to Practitioners

There is no single predefined path to designing symbols for automated driving systems, but hopefully the following recommendations can help guide designers, engineers, or researchers in their future endeavours. I hereby propose five points of reflection to apply in one's research or design process to 'design around the concept of affordance.'

① *understand the driver*: using participatory design can be a useful method to access the content of drivers' mental representations, whether this content ends up being neglected or highlighted in future stages. Using UCD concurrently or posteriorly can also help inform how drivers see the world.

② *understand the signifiers*: what matters is what the driver sees, not the engineer. One should be aware of the signifiers that are relevant to the driving task, and especially those that are relevant to the aspect that is to be automated by the system. For instance, the design of lane markings in a lane-keeping system symbol can change the interpretation of the symbol to reflect more what the design would mean for a driver in real life. UCD can be a good tool to assess how several variants of a symbol could be interpreted. How a system technologically operates is not as useful and is too ambiguous to be central to a symbol: for instance, ACC is not the only system using RADAR waves and depicting this technology does not inform of what the system does.

③ *understand the system*: what matters is what it does and what it does not. If it is possible to depict a system's behaviour in a symbol, it could be useful to the driver to easily understand it, memorise it, and identify it. Using abstract signs can achieve this and symbols do not need to be restricted to concrete elements (see Marcus, 2003).

④ *understand the ecosystem*: what do the other systems do that this one does not. One should be mindful that a symbol will appear in an ecosystem of symbol, and that one system might appear along very similar systems. It might therefore be useful to focus on how these systems differ in terms of capabilities and limitations, or in terms of use and experience affordances (see Pucillo & Cascini, 2014).

Finally, ⑤ ***afford stories***: eventually, and according to drivers preference, the symbols should tell stories; not only independently but also collectively. Ideally, a symbol should tell the driver what would happen after a particular system is activated and how the other systems may complement it or supplant it.

VI. Final Conclusion

Designing symbols and interface elements for driving automation systems should not be approached like designing logos and phone applications, for which safety is not a concern. Symbols and HMIs should not be aesthetically pleasing without being usable and useful. They should not be designed by illustrators uninformed about human factors and uninformed about or by future users. Hopefully, the research, guidance, and regulation regarding these aspects of vehicles equipped with automated driving features will develop rapidly in the near future and push the market towards more harmonisation and towards innovation. Standardisation has the known benefits of increasing the reliability, predictability, and safety of consumer products, as well as making the production and evaluation processes of these products easier for manufacturers and regulators, respectively. While standardisation may seem like it is constraining the development or refinement of certain aspects of a vehicles, constraints are suspected to drive creativity and innovation (Acar et al., 2019). Brands, in their approach towards differentiating themselves from competitors, may start to look towards innovating in other aspects such as improving energy efficiency, new active safety features, or passive safety of the vehicle—the Euro NCAP, for instance, conducts regular evaluations of new vehicles in their abilities to avoid or mitigate collisions for both occupants and vulnerable road users. Brand differentiation starts to become an issue when it defies the harmonisation of how systems operates and render the transferability of mental models difficult or impossible. It is in situations such as this one that standardisation becomes capital and research such as this one, necessary.

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