Guidelines safe HMI design

Deliverable D4.2– WP4 – Public

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 814735.

Guidelines safe HMI design

Work package 4, Deliverable D4.2

Please refer to this report as follows:

Grondelle, E.D. van, Egmond, R. van, Muthumani, A., Tofetti, A., and de Goede, M. (2023). Guidelines safe HMI design, Deliverable D4.2 of the H2020 project Mediator.

Project details:	
Project start date:	01/05/2019
Duration:	48 months
Project name:	MEDIATOR – MEdiating between Driver and Intelligent Automated Transport systems on Our Roads
Coordinator:	Prof. Dr. Nicole van Nes | SWOV – Institute for Road Safety Research Bezuidenhoutseweg 62, 2594 AW, The Hague, The Netherlands
	This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 814735.

Deliverable details:	
Version:	Final
Dissemination level:	PU (Public)
Due date:	30/04/2023
Submission date:	30/04/2023

Lead contractor for this deliverable:

Elmer D. van Grondelle – Delft University of Technology

Mediator

Report Author(s):	Van Grondelle, E.D., Van Egmond, R. – Delft University of Technology, The Netherlands De Goede, M. – SWOV Institute for Road Safety Research, The Netherlands Muthumani. A – Autoliv, Sweden Tofetti, A. – Stellantis, Italy

Revision history

Date	Version	Reviewer	Description
31/03/2023	Reviewed draft	Tal Oron Gilad – Ben-Gurion University of the Negev	Internal review
16/04/2023	Reviewed draft	John D. Lee - University of Wisconsin-Madison	External Review
30/04/2023	Final draft	Ernst Verschragen (QA officer) – SWOV Institute for Road Safety Research	Final editing and checks
30/04/2023	Final deliverable	Michiel Christoph (Technical project coordinator) – SWOV Institute for Road Safety Research	Approved

Legal Disclaimer

Table of contents

Abbreviations and glossary

AD	Autonomous Driving
ADS	Automated Driving System
Assisted driving	Mediator’s HMI autonomous driving level, comparable to SAE 1 and 2
CM	Continuous Mediation
DL	Decision Logic is the central component of the Mediator system that processes Automation State, Driver State, and Driving Context information, into HMI input on e.g., mode changes, and corrective actions.
HF	Human Factors
HMI	Human Machine Interface
Manual driving	Mediators’ HMI driving mode comparable to SAE level 0
NDRA	Non-Driving Related Activity
NDRT	Non-Driving Related Task
ODD	Operational Design Domain
OEM	Original Equipment Manufacturer i.e., car manufacturer
Piloted driving	Mediator’s HMI autonomous driving modes comparable to SAE 3 and 4
SAE	Society of Automotive Engineers
TI	Technology Integration
Tier 1, 2, *	Automotive Industry supply chain to the OEM
TtS	Time to Sleep

List of Figures

Preface

This is the final HMI design deliverable of the MEDIATOR project. In this four-year H2020 project we have forwarded from knowledge gaps to functional requirements, to design requirements, and finally towards recommendations for HMI design in partially autonomous driving for policy makers, legislators, and other stakeholders.

We are confident in, and proud of our achievements. We feel we have mitigated the pandemic's substantial and continuous impact throughout the project successfully, and despite the hurdles, we grew into a solid consortium with close bonds. Surely that is one of the reasons that we have been able to mitigate the domino effect of delays throughout the project in this final task.

Contributing partners to this document are listed as authors. However, explicit credits are due to Maartje de Goede (SWOV), who was parachuted into the project very late to compensate for risen staffing issues, familiarized herself with the project overnight and proved indispensable in writing this deliverable. Many thanks also for their flexibility and perseverance to our internal and external reviewers Tal Oron Gilad (BGU), and John D. Lee of the University of Wisconsin-Madison.

Elmer D. van Grondelle

Task Leader

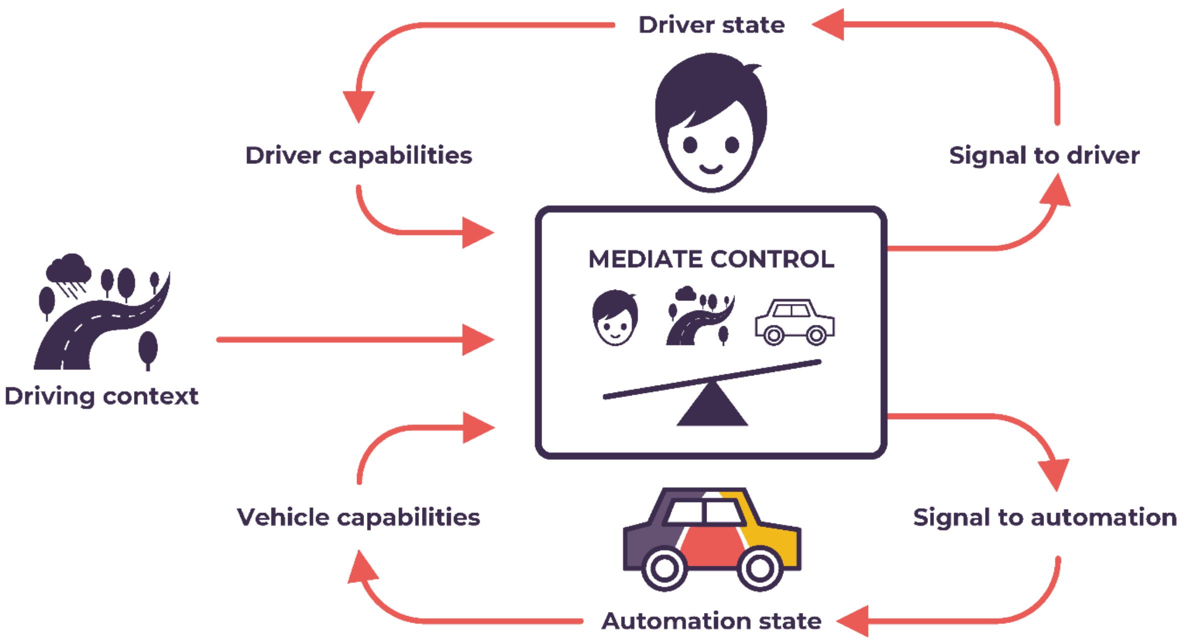
About Mediator

MEDIATOR, a 4-year project coordinated by SWOV Institute for Road Safety Research, has come to an end after four years of hard work. The project has been carried out by a consortium of highly qualified research and industry experts, representing a balanced mix of top universities and research organisations as well as several OEMs and suppliers.

The consortium, supported by an international Industrial Advisory Board and a Scientific Advisory Board, represented all transport modes, maximising input from, and transferring results to aviation, maritime and rail (with mode-specific adaptations).

Vision

Automated transport technology is developing rapidly for all transport modes, with huge safety potential. The transition to full automation, however, brings new risks, such as mode confusion, overreliance, reduced situational awareness and misuse. The driving task changes to a more supervisory role, reducing the task load and potentially leading to degraded human performance. Similarly, the automated system may not (yet) function in all situations.



The Mediator system will constantly weigh driving context, driver state and vehicle automation status, while personalising its technology to the drivers' general competence, characteristics, and preferences.

The MEDIATOR project aimed to develop an in-vehicle system, the Mediator system, that intelligently assesses the strengths and weaknesses of both the driver and the automation and mediates between them, while also taking into account the driving context. It assists the timely take-over between driver and automation and vice versa, based on who is fittest to drive. This Mediator system optimises the safety potential of vehicle automation during the transition to full (level 5) automation. It would reduce risks, such as those caused by driver fatigue or inattention, or on the automation side by imperfect automated driving technology. MEDIATOR has facilitated market exploitation by actively involving the automotive industry during the development process.

To accomplish the development of this support system MEDIATOR integrated and enhanced existing knowledge of human factors and HMI, taking advantage of the expertise in other transport modes (aviation, rail and maritime). It further developed and adapted available technologies for real-time data collection, storage and analysis and incorporated the latest artificial intelligence techniques. MEDIATOR has developed working prototypes, and validated the system in a number of studies, including computer simulation, virtual reality, driving simulator and on-road studies.

With MEDIATOR we further paved the way towards safe and reliable future vehicle automation that takes into account who is most fit to drive: the human or the system.

https://mediatorproject.eu/

Executive summary

This document, one of the final deliverables of the 4-year MEDIATOR project, formulates general recommendations on HMI design for semi-automated and highly automated vehicles, to obtain safe interactions between the driver and the driving system. HMI is one of mediator's main components, next to Automation State, Driver State, and Decision Logic which is the central component that mediates in between, based on who is most fit to drive. In this project, the HMI is composed of all components that interact with the driver visually, auditory, and haptically.

Framing of the project

Knowledge gaps

At the beginning of the MEDIATOR project, knowledge gaps have been identified and prioritized for further research. Five knowledge gaps have been designated as primary, which are Transfer of control, Transparency and Information Overload, Keeping the Driver in the Loop, Conflict Negotiation, and OEM Design Space. Additionally, secondary knowledge gaps that could be investigated within the primary studies are Intuitive Learning, Long term effects i.e., Skill Degradation and Complacency, and Human Driver Characteristics.

HMI Design Guidelines

To frame the HMI design process, five initial HMI design guidelines have been defined:

- **Embrace a holistic approach** entails two main principles. Firstly, the Mediator HMI facilitates and manages all interaction components between human and vehicle for both primary, driving-related tasks as well as for most secondary tasks like climate control or entertainment. Secondly, mode awareness is elicited by the entire (holistic) experience of the driver by ambient lighting.
- **Design a generic transfer ritual** entails the principle, that all interaction between the Mediator system and the driver are constructed in a single ritual i.e., a way of doing something in which the same actions are done in the same way every time, to facilitate quick intuitive learning and minimizing the risk of bias. While the sequence of the ritual up to e.g., a control transfer is always the same, its elements i.e., three signals and two time-intervals in between, are variable in their timing, intensity, and modality.
- **Design for learned affordances** assures that HMI design is compatible with current and future standards for HMIs for ADS and in line with users' intuitive expectations. A learned affordance relates to an existing knowledge and experiences and therefore suggest an object's function and how it should be used. Learned affordances (standardisation) are essential to overcome issues related to learning new (driving) skills, process the complexity of information and reduce cognitive response time.
- **Design for user acceptance** surpasses the common assumption in autonomous driving research and design projects, is that a driver's suitability to control the vehicle is being determined by the system. While the HMI plays a crucial role in driving perception (mode awareness) and driving behaviour, its success depends on its ability to establish trust, provide comfort, and facilitate driver autonomy, all of which are interdependent.
- **Design for industry acceptance** is important because the automotive industry is structured by, and built on, so-called brand identities. Hence, the importance of expressing brand identity through design is fundamental. Therefore, design space which allows to

adapt HMI design to a specific industry brand identity is deemed crucial for industry acceptance.

Mediator autonomous driving modes

Although the SAE distinguishes six driving modes, in Mediator we have recognised three driving modes i.e., Continuous Mediation (CM; comparable to SAE L2), Stand-by (SB; comparable to SAE L3) and Time to Sleep (TtS; comparable to SAE L4). From a human factors' perspective, and with respect to a transfer period which will include 'conventional' vehicles, in the Mediator HMI design these have been transformed into Manual, Assisted and Piloted driving.

The main feature of the HMI is its ambient lighting to evoke mode awareness, in which Assisted driving is expressed through high-luminosity amber, and Piloted driving though lower-luminosity purple. Those colours are applied consistently in HMI design in e.g., time-budget representation on the display and the countdown towards a mode transfer by led strips in the steering wheel.

Methods

The HMI is developed in a research-by-design process with several design iterations, in which the design is merely a means to research. Versions of the HMI have been tested in VR studies, mock-ups, simulator testing and on-road trials. Testing was done by ten original use-cases with derivatives for specific ODDs, representing as much as possible the infinite number of possible use-cases. The design process and studies were furthermore driven and supported by research into existing HMIs, literature research and expert opinions, and stakeholder workshops.

Transition of control

Well-designed transitions between different levels of automation are of utmost importance in establishing a safe interaction between the driver and the system (Lu, Happee, Cabrall, Kyriakidis, & de Winter, 2016). HMI concepts have been developed that deal with preparing the driver for an upcoming takeover, informing the driver on the upcoming takeover, the timing of the takeover as well as on the urgency of the takeover. All types of transfers are based on the Mediator template ritual. While its components are fixed, the values of each component vary.

An effective way of communicating transfers to the driver in the Mediator HMI appeared to be LEDs in the steering wheel accompanied by haptic and other audio-visual information. An appreciated aspect was a visual countdown of the LEDs, indicating the time left before a required takeover.

The following recommendations have been derived to address this knowledge gap:

- An HMI should have a basic ritual for all changes and transfers. The template is fixed but the values of each component vary.
- Fitness of the driver, and of the driving system, should be continuously communicated.
- Personal adaptation of warning-timings in takeovers should be possible.
- Latencies between a signal and driver response should be optimized in relation to urgency and human reaction times / expectations.
- The intentions of the vehicle and the reasons for a takeover during automated driving should be clearly communicated to the driver.
- When a transfer to manual control is required, an HMI should support the driver in preparing for takeover. For example, after a 'wake-up call' the driver should remain attentive before the actual takeover finds place.
- In case the driver must regain control and the urgency level is high, the takeover request should be communicated by means of multi-modal intrusive signals.

- Apply a visual countdown instead of a constant or single-frequency signal, to indicate a takeover procedure.
- A visual countdown, through led or otherwise, must be positioned in the primary sightline of the driver i.e., on the steering wheel.
- Use colour codes with a dynamic pattern for request messages such as 'automation available', 'activating automation', and 'automated driving is activated' (see also Section 3.2).
- Use distinct colour codes to convey the vehicle mode or level related information (see also Section 3.2).
- A planned takeover, signalled by a visual countdown, must be supported by additional signals, such as seat-vibration, and textual or auditory messages to guide users through the actual take over.

Transparency & information overload

A great risk of mode confusion is that drivers misjudge their own tasks and responsibilities (Tinga, Cleij, Jansen, van der Kint, & van Nes, 2022). One way to establish mode awareness is to make the system transparent i.e., a system that provides sufficient and clear information to the driver about the functioning of the system. On the other hand, drivers should not experience an information overload that reduces driver comfort and decreases the ability to perceive and process new information. An HMI should be designed in such a way that this delicate trade-off between transparency and information-overload is optimally balanced in all situations.

Several Mediator HMI concepts have been developed to establish this delicate trade-off. Based on the finding that drivers prefer information on the automation status above information on the desired driving task the concept of ambient lighting has been developed. Indicating the current mode, the time left to next mode and the anticipated time in the next mode (i.e., time budget) addressed the user's desire for anticipatory information.

Findings addressing this knowledge gaps resulted in the following recommendations:

- The HMI must communicate the current driving-mode continuously and in a holistic way. This can be achieved, for example, through ambient lighting (see 3.2).
- The HMI should communicate the time left in current mode/time to next mode continuously while clearly signifying the current mode. This can, for example, be attained through communicating the time in a number, or, through a LED bar depleting over time with decreasing time in the mode.
- When the current mode will change to another mode the HMI should communicate the reason for this change in advance. This requirement can be attained by for example using icons for an event that will occur in the environment, for example indicating that roadworks ahead, or that the car will leave the city.
- The HMI should nudge and/or inform the driver about what to do. Especially drivers that have not much experience with the driving system should get explicit information (for example, icons or spoken text) next to non-intrusive implicit information (for example, ambient lighting).
- Design ambient awareness with different colour codes to continuously inform the driver in a non-intrusive way of the current automation level.
- Ambient lighting should, especially with inexperienced drivers, be accompanied by other types of information (for example visual/auditive information) on automation levels/modes.

- Continuously communicate the time budgets in the current mode as well as, the upcoming driving mode.
- The symbols and colours of the different driving levels shown in the time-budget widget should be consistently used throughout the ambient communication of the different driving levels (such as ambient lighting).

Keeping the driver in the loop

Partial automated driving requires the driver to continuously monitor the driving situation. Next to mode awareness a major challenge is keeping vigilance in monitoring. Vigilance deterioration i.e., driver unfitness can be caused by task overload (active fatigue), task underload (passive fatigue), sleepiness as well as distraction. In the MEDIATOR project corrective as well as preventive HMI concepts have been applied that address fatigue (task underload & sleepiness) as well as distraction.

In one Mediator evaluation simulator study a non-driving related trivia task was used as a preventive measure for fatigue due to underload during assisted driving. In this simulator study, an auditory and visual Trivia game was used to prevent task underload (passive fatigue). The invitation to play the game appeared on the infotainment display when fatigue was monitored or suspected, respectively as corrective, or preventive measure. Although, fatigue-related differences were not found between the Trivia- and non-Trivia groups, the Trivia game appeared to support maintaining situational awareness.

In three further (two on-road and one simulator) Mediator evaluation studies HMI warning concepts in case of distraction or fatigue have been tested, based on the Mediator generic transfer ritual.

If fatigue was detected, a degraded fitness message was shown on the displays and an audio alert was triggered. In the on-road trial also a cushion in the seat was inflated to give the participant a more upright position as well as a gentle vibration in the seatbelt. Warnings were escalated if needed, visually, auditory and with seatbelt vibration. A similar procedure was carried out if distraction was detected, but with a corresponding distraction message instead of a degraded fitness message. In case a suitable (higher) level of automation was available in case of distraction, the Mediator advertised the concerning driving mode. Results indicated that the suggested mode switch with alert messages somewhat reduced task-related fatigue but not sleep-related fatigue. Next to some criticism towards the specific working of HMI components, the results also indicated that the Mediator HMI, including distraction warnings, resulted in less distraction in assisted driving compared to a baseline HMI, with no distraction warnings.

A haptic seatbelt (pull) was introduced in the Mediator HMI because haptic feedback can effectively redirect visual attention to time-critical events or important information. The part of the seatbelt that touches the lower part of the torso contains a seatbelt pull force that is activated in case of an emergency/unplanned takeovers. Evaluations showed that the haptic feedback of the seatbelt is effective.

The following design recommendations have been derived for this knowledge gap.

- The availability of an optional and conditional NDRT in the HMI is recommended.
- Alert messages should be designed according to a generic (see Chapter 2) escalation ritual.
- Alert messages should consist of multi-modal signals, such as acoustic signals, text messages, and seatbelt vibration and visual signals.

- Alert messages should be accompanied by suggestions or instructions of actions to be taken by the driver.
- Apply haptic seatbelt feedback in case of emergency or unplanned takeovers as well as in case of distraction. The force of the seatbelt feedback should be adjusted to the weight and length.

Negotiation conflicts

While acknowledging driver autonomy as a key element of comfort, interrelated with trust, and therefore crucial for user acceptance, it surfaces the need to negotiate disagreements between the driver and the automation system over whom should take control. Based on human negotiation styles the implementation of the negotiation ritual in the HMI encompasses an interaction flow and a force feedback mode shifter.

The negotiation routine is evoked in the standard ritual, whenever a driver does not comply with the, driving mode, that is by advocated the system. Depending on the reason for the advocated driving mode, which may be comfort driven or safety driven, respectively seductive negotiation is deployed or a somewhat more rigorous persuasive negotiation. In case of the latter, and upon driver persistence to choose a driving mode that is not advocated, the system may initiate counter measures like e.g., limited vehicle performance in acceleration or speed.

A crucial HMI hardware component in Mediator's human machine negotiation is the Force Feedback Shifter. A conventional automatic gear shifter, in compliance with learned affordances, is expanded with Mediator's two automated driving modes, Assisted and Piloted. Its force feedback mechanism resists mode selections that are discouraged by the system, and blocks mode selections that are not available.

The following design recommendations have been derived for this knowledge gap:

- The need for, or the value of, driver autonomy is generally confirmed.
- Countermeasures that reward a driver's regular compliance with DL advertised autonomous mode like parking benefits, work better than negative countermeasures, such as reducing a vehicle's performance in terms of speed and acceleration.
- The reason for a by DL advised autonomous mode must be communicated to the driver. This contributes to the negotiation outcome and calibrates trust.

OEM design space

For industry acceptance, diversification in brand identity i.e., brand specific design of the human-product interaction, and manifestation of the HMI system (behaviour, look and feel) are crucial. In the MEDIATOR design process this means that we aimed to identify design space i.e., applicable value ranges and variation in visual, auditory, and tactile design, rather than single values. For this knowledge gap, unfortunately, the initial research plan could not be completely fulfilled because of extensive COVID-19 restrictions at the key partner. Further research is foreseen.

However, from the regular interaction, and particularly from the stakeholder workshops we suspect that design space can be facilitated as Mediator's HMI has been built in various compositions and designs of its components, be it within the design guidelines and with respect to e.g., the designated HMI ambient light colours. The leading question was, what is required to ensure safety?

The following general design recommendations have been derived for this knowledge gap:

- In the development of legislation or design recommendations, it is important to acknowledge the OEM design space, so that brand identity can be conveyed.

- The transfer of control ritual must be similar across vehicles.
- In case of mode awareness through ambient colours, colour coding must be similar across vehicles and brands. Colours cannot have another meaning from one vehicle to the next.
- Information on autonomous driving modes in the context of mode awareness, learning and information overload, must be standardised across all brands.
- It is important to acknowledge that brand experience includes, next to visual, auditory, and haptic experience, also a brand appropriate HMI behaviour through e.g., vehicle dynamics.

Conclusions

Five HMI design guidelines have been defined to form the basis of designing an HMI that establishes a safe interaction between a semi-automated driving system and a human driver. Based on the evaluations of the developed Mediator HMI concepts, main conclusions and recommendations per guideline are described.

Embrace a holistic approach

The safety of a partially automated driving system is based on the driver being continuously aware of the current driving mode and the related responsibilities of the driver, as well as the system's capabilities and limitations. Holistically communicating driving modes should enable continuous awareness in a non-intrusive way and without needing much information-processing capacity. Holistic communication of the driving modes can, for example, be established by ambient lighting as was done in the MEDIATOR project.

Design a generic transfer ritual

Predictability of a system is essential in establishing an interaction that is trusted, reliable, and comprehensible. Therefore, within the MEDIATOR project, a standard ritual was developed based on which HMI information flows to address the different use-cases were designed. The results showed that the Mediator ritual was generally appreciated and understood by users providing a strong indication that a fixed ritual is valuable.

Design for learned affordances

Relate concepts and activities to existing knowledge and experience of people saves mental energy and therefore increases chances that people may perform these new activities safely. Within the MEDIATOR project the HMI concepts were, as much as possible, based on existing affordances, such as concrete icons, the application of the gear shifter in transferring between modes, a seatbelt pull to indicate urgency, and escalating sound patterns in case of an urgent takeover request.

Design for user acceptance

Driver autonomy is deemed crucial for user acceptance of partially autonomous vehicles. Specifically, in the case of negotiations, information on the reason for a proposed autonomous mode by the DL, is important to evoke trust and persuade the driver to follow the recommendation.

Design for industry acceptance

The validity and importance to construct legislation and guidelines such that the design space to express a brand identity is being confirmed. At the same time, it became clear that there are limitations, specifically if it comes to mode transfers and mode awareness across vehicles and across brands.

Limitations & recommendations for future research

Further research that has derived from the Mediator studies concerns:

- The determination of optimised timing intervals in transfer rituals, that are dynamic because of real-time changes to its parameters and because they are likely to be subject to individual driver preferences.
- While we have surpassed our intended studies on driver-automation negotiations, the interesting outcome implies that more research into the exact working of such a negotiation in the HMI requires more design concepts and more studies.
- Although the need for design space with respect to automotive branding has been acknowledged, more studies as they intended before the pandemic, are still due, to determine more specifically the limits of how to balance cognitive response with brand experience.
- With respect to the knowledge gap Human Driver Characteristics, the common finding across MEDIATOR studies that adaptation to individual driver preferences is important, further research will provide inside into the determination of personal preferences and implementation of an adaptive HMI.
- From the common finding throughout the MEDIATOR studies is that for completely new functionalities, some form of driver education or instruction is needed, further research is needed into the design of HMIs that have instructive or education functionality.
- Research into the long-term effects of Mediator like systems, through longer and larger studies, must provide knowledge for designing HMIs that can benefit from those positive, or mitigate negative effects.
- The holistic approach towards HMI design, in principle, leads to more valuable research results because it allows to test and validate all elements in their realistic context. However, collecting quantitative data requires much larger studies in all their aspects e.g., sample and duration. Further larger studies are expected to validate quantitative studies thoroughly.

For further reading

The document structure is similar to the headings in this Executive Summary. HMI design guidelines for specific knowledge gaps are listed per chapter. General design guidelines are listed in the Conclusions chapter.

1. Introduction and framing principles

This is the final MEDIATOR deliverable on HMI design, in the work package Impact and Recommendations. In MEDIATOR the Human Machine Interface (HMI) is considered to facilitate all interaction between the driver and the Decision Logic (DL). In contrast to the general perception of an HMI limited to the instrument panel, it basically implies that the whole interior of the vehicle is considered HMI. Its main functions are communicating with the driver and informing the driver on conventional driving tasks and control transfers (takeovers), executing preventive and corrective measures regarding driver fitness, and facilitate negotiations between driver and automation. The HMI design is therefore crucial in coordinating a safe interaction between the driver and the driving system.

The aim of this deliverable is to formulate general recommendations for (semi-) automated driving systems to obtain safe interactions between the driver and the driving system. A safe interaction is defined here as an interaction that is experienced as predictable, comprehensible, and trusted, and takes in account to the capacities and preferences of the driver. (Christoph et al. (2019).

The proposed recommendations are based on the developed knowledge and HMI concepts within the MEDIATOR project, and on MEDIATOR's core idea to always mediate between driver fitness and automation fitness with regards to its context. In this report we discuss the HMI concepts' characteristics deemed to influence the user's perception, experience and/or behaviour. The theoretical knowledge underlying the development of these concepts is touched upon but discussed in detail in other MEDIATOR deliverables: Christoph et al. (2019) and E.D. van Grondelle et al. (2021).

Whereas in this deliverable the practical implications of the evaluations of the different HMI concepts are being discussed, evaluations of the Mediator system (including its HMI) are discussed in detail in two other MEDIATOR deliverables: Borowsky et al. (2023a) and Borowsky et al. (2023b).

Knowledge gaps

At the beginning of the MEDIATOR project, after an initial literature study, knowledge gaps have been identified and prioritized for further research. In the prioritization five of those knowledge gaps out of eight have been earmarked as primary. With respect to expertise and allocated resources, those have been assigned to leading partners, while the remaining 'secondary' three have been designated to be investigated within the primary knowledge gaps, upon opportunity and appropriateness (Christoph et al., 2019).

Knowledge gaps that were earmarked as primary are:

- Knowledge gap 1, Transfer of control
- Knowledge gap 2, Transparency and Information Overload
- Knowledge gap 3, Keeping the Driver in the Loop
- Knowledge gap 4, Conflict Negotiation
- Knowledge gap 5, OEM Design Space

The fifth knowledge gap, intended to be investigated once the HMI design was considered as mature in this project, could not be fully investigated as intended due to COVID-19 restrictions within key partners. Instead, we have collected the necessary input in the stakeholder workshops that were organised early 2023.

Knowledge gaps, earmarked as secondary and addressed as much as possible within other studies are:

- Knowledge gap 6, Intuitive Learning
- Knowledge gap 7, Long term effects i.e., Skill Degradation and Complacency
- Knowledge gap 8, human driver characteristics

For Intuitive Learning the studies have provided sufficient outcomes to determine HMI Design Guidelines. As Skill Degradation and Complacency would require much longer studies, and Driver Characteristics would, next to a longer trial duration also need a much larger sample, those knowledge gaps could not be investigated sufficiently because of the COVID-19 impact on the project.

On the other hand, there have also been opportunities to go beyond the intended research. For example, on human-machine negotiations in case of conflict, we have been able to do a research-by-design iteration, while no further specific studies than a literature study that was promised.

HMI design guidelines

To frame and guide the detailed design process (Grondelle et all, 2021) five preliminary design guidelines have been defined in the earliest project phase, explained in Section 1.1. Also defined quite early in the project, is our approach towards driving modes from a human factors' perspective, in contrast to the engineering-based SAE driving modes. The HMI autonomous driving modes derived from this HF approach, are explained in Section 1.2. Section 1.3 is an overview of the applied methods.

Document structure

In this report, findings and guidelines are organized according to the defined primary knowledge gaps or HMI challenges (see Chapters 2-6). Studies often also provide findings on additional knowledge gaps than the one the study was designed for. If so, this has been noted.

In the different chapters, guidelines are defined based on evaluations of specific HMI concepts as well as findings on the Mediator-HMI characteristics in general. Evaluations of the entire Mediator system (as discussed in MEDIATOR deliverables 3.3 and 3.4) will not be discussed in case these findings cannot be related to specific HMI concepts or characteristics. A short summary of the general conclusions i.e., general design guidelines and the anticipated next steps is provided in Chapter 7.

1.1. Preliminary HMI design guidelines

Five design guidelines have been determined early in the MEDIATOR project to frame the HMI research and design. They have been derived from design practice, design experience, and literature research. The Design Guidelines are justified in detail and described in D1.5 HMI Functional Requirements (Christoph et al., 2019) and briefly explained here:

Embrace a holistic approach

The Mediator HMI facilitates and manages all interaction components between human and vehicle for both primary, driving-related tasks as well as for most secondary tasks like climate control or entertainment. For example, drawing attention to an HMI signal is more effective when e.g., the potentially distracting entertainment system is interrupted simultaneously.

Furthermore, in the Mediator HMI design, mode awareness or responsibility awareness is elicited the entire (holistic) environment of the driver, by ambient lighting and a consistent application of colours related to the driving mode.

Design a generic transfer ritual

In principle, the interaction between the Mediator system and the driver and the information provided to the driver must be tailored to each use-case, to evoke adequate driver fitness and actions within the available timeframe.

Tailoring to a multiplicity of use-cases, however, will not facilitate intuitive or quick learning. Therefore, all interactions are constructed in a single ritual i.e., a way of doing something in which the same actions are done in the same way every time. Structural application of the same components, in a standard sequence, and consistent visualization of the template in use-cases, design processes and experimentation assure comparability, thus minimizes the risk of bias.

The control transfer ritual (transfer from the system towards the driver and vice versa), Figure 1, foresees three signals, the third of which is also the action, with two specific time intervals in between. A more detailed flowchart, including mitigation in case of an unresponsive driver, can be found in Section 1.4.1. While the interaction ritual or process is always similar thus expected and instinctively anticipated by the driver, its components (time-intervals and signals) are variable, depending on time budget and driver response, as indicated by Decision Logic. In the Mediator design process, the behaviour of all HMI components has been designed for every single use-case in seven steps i.e., situation before, the three signals (in ascending urgency; grey, orange, and red) and two time-intervals (orange and red) form the ritual, and the situation after.

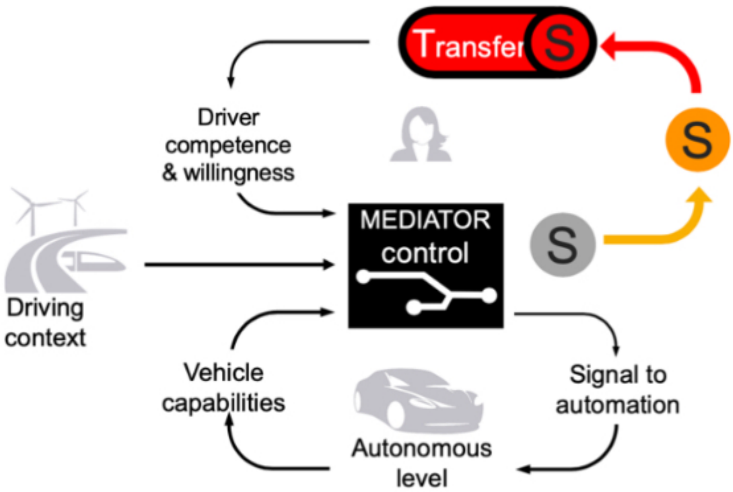


Figure 1 Generic control transfer ritual positioned in the Mediator system.

Design for learned affordances

It is important that the HMI design is compatible with current and future standards for HMIs for ADS and in line with users' intuitive expectations, as well as understandable for all drivers, independent of, for example, linguistic and IT abilities (Fiorentino et al., 2023). Thus, the design should be such that any licensed driver is able to use the HMI effectively and safely in any vehicle.

In design, according to Normann (1988) an affordance is the design aspect of an object which suggest how the object should be used i.e., a visual clue to its function and use. A learned affordance relates to an existing knowledge and experiences and therefore suggest an object's function and how it should be used. Learned affordances (standardisation) are essential to overcome issues related to learning new (driving) skills while conventional driving skills remain. Learned affordances are also essential to process the complexity of information and reduce cognitive response time.

Given that the Mediator HMI will combine conventional driving skills with new driving skills, new functionalities will be added that are unfamiliar to the conventional automotive HMI. In that case the design directive would be to build on general known affordances in such a way, that they do not conflict with long-time learned affordances.

Design for user acceptance

A common assumption in autonomous driving research and design projects, is that a driver's suitability to control the vehicle is being determined by the system, based on a complexity of parameters that are either known about the driver or measured in real-time. In this line of thought the system decides unilaterally who has control over the vehicle, driver or automation. This disqualification of driver autonomy is in sharp contrast with the acquired status-quo of driver autonomy. While the HMI plays a crucial role in avoiding misunderstandings, misuse, overreliance, reduced situational awareness, and mode confusion, its success depends on its ability to establish trust, provide comfort, and facilitate driver autonomy, all of which are interdependent.

Design for industry acceptance

The automotive industry is structured by, and built on, deeply rooted emotional values of automobility such as status and adventure, which are captured in brand identities. Autonomous driving technology is a short-term business opportunity to create strategic advantage. In the long-term, however, autonomous driving systems are also expected to further diminish differentiating properties between brands. This poses a risk towards branding, the aim of which is to offer customers a unique distinctive proposition. Therefore, for industry acceptance, diversification in brand identity i.e., brand specific design of the of the HMI system (look and feel) are crucial for market penetration (Fiorentino et al., 2023).

In the MEDIATOR design process this means that we identify design space, meaning applicable value ranges and variation in visual, auditory, and tactile design, rather than single values. As a restriction, variation in design is perceived to be unwanted in urgent or emergency scenarios.

Another concern for industry acceptance is cost. As vehicle technology becomes more complicated, controlling manufacturing cost towards feasible sales pricing becomes more difficult. Although not the primary concern in the HMI design process, the Mediator HMI design is composed of only nine components from an initial inventory of more than fifty potential technologies to anticipate exploitation (Fiorentino et al., 2023). Moreover, out of those nine components are already present in vehicles or need only moderate functionality adaptation.

1.2. Mediator Autonomous Driving Modes

Although the SAE distinguishes six driving modes, basically defined by adding technologies, from a Human Factor perspective, learning six different compositions of technology and understanding, and appropriately displaying, six variations of driver responsibility is unwanted. In MEDIATOR we have recognised three driving modes i.e., Continuous Mediation (CM comparable L2), Stand-by (SB comparable to L3) and Time to Sleep (TtS comparable to L4).

SAE	0	1	2	3	4	5
	Driver supported			Automated driving		
Automation responsibilities	warnings and momentary assistance	steering or brake/ acceleration support to the driver	steering and brake / acceleration support to the driver	Automated driving features will take care of driving under limited conditions when all required conditions are met		It is taken care of driving under all conditions
Human responsibilities	driver must constantly supervise			When requested, driver needs to drive	It is not required to take over driving	
Euro NCAP		Assisted		Automated		Autonomous
		Shared control		Vehicle in control		
Automation responsibilities		OEDR and other supportive task.		OEDR & driving. Vehicle has full responsibility		Full control
Human responsibilities		OEDR & driving. Driver is fully responsible. No ST.		Driver can do NDRT, but needs to be available for a safe transfer of control		driver is a passenger.
Mediator	CM			SB	Tts	
		(Driver in the loop) "assisted driving". Drivers are responsible but supported by the automation. Driver has monitoring task		(Short out of the loop) "conditional automation". Driver needs to take back control when needed.	(Long out of the loop) "high level of automation" Drivers can immerse themselves in NDRT	
HMI	Manual	Assisted		Piloted		
	non-automated, driver is in full control	User is not fully out of the loop and has to maintain certain responsibilities (DDT). This can be steered towards a monitoring task.		Driver monitors while automation performs driving tasks		

Figure 2 Comparison between SAE, Euro NCAP, and MEDIATOR automation levels, how they are communicated by the HMI, and by which ambient colour coding.

In the HMI this Human Factor's perspective has been translated into three automation levels with names that are easier to comprehend by users i.e., Manual, Assisted and Piloted. Firstly, while in the Human Factors perspective conventional vehicles always offer at least some level of CM functionality, in the HMI we explicitly distinct Manual driving mode for two reasons.

- Firstly, to confirm people's perception of vehicles with and without autonomous driving functionality.
- Secondly, because of the transfer period in which conventional driving vehicles will interact with those with autonomous capabilities, and more importantly, because people may switch from one to the other, it remains important to explicitly acknowledge those different vehicle capabilities.

Assisted and Piloted are equally comprehensible names. Assistance implies a shared task and equals CM, up to SAE level 2. Piloted driving comprises SB and TtS, represented to the driver as single choice to keep the number of selectable modes as low as possible, as indicated in our earlier trials and confirmed in our stakeholder workshop with governmental and vehicle approval authorities. In Piloted mode the HMI will automatically scale up from SB to TtS when the central Decision Logic module considers that available in terms of driver fitness and automation fitness, and in terms of duration (comfort), and adjust the driver's environment accordingly.

1.3. Approach

The HMI research and design process i.e., to design and build the component(s) that interact with the human driver is framed by several starting points:

- MEDIATOR use-cases. Ten original use-cases (see E.D. van Grondelle et al. (2021)) with derivatives for specific ODDs resulted in seventeen use-cases in total, composed such that they represent the infinite number of possible ODDs as complete as possible.
- HMI functional requirements that have been formulated per use-case. Additional research was done for those use-cases for which the design requirements needed further specification (E.D. van Grondelle et al., 2021).

- Design Guidelines, as described in Section 1.1 above.
- MEDIATOR's autonomous driving modes, as described in Section 1.2 above.

1.3.1. Methods

The Mediator HMI is developed, using different methods.

Research by design strategy

Research by Design is a method in which concept designs are not the goal in themselves. They facilitate experimentation and research (Stappers & Giaccardi, 2017). In the earlier stages of the project, a sequence of concept designs was created in a continuous iteration of rapid HMI design projects. While some of those concepts were designed to assess the HMI integral design, other iterations focused on specific knowledge gaps from the literature studies such as takeovers or conflict mitigation.

Research by Design was chosen as a strategy because it fits the dynamic of a design process better in that it allows for multiple iterations, throughout the project and from the beginning. Rapid Design iterations were facilitated by overlapping master-student graduation projects of generally six months each. Despite administrative limitations (Fiorentino et al., 2023), the advantage of this is threefold:

- Because each design project is performed by another designer (graduation student), new thinking and new ideas enter the design process. Those ideas are either of direct value or help to build a design inventory from which to benefit later.
- Because in each graduation project the graduation student is coached by a team of his or her own choice, and based on the specialism that is most appropriate for the challenge, a wide variety of specialisms feed into the project beyond its regular consortium members.
- Each design iteration encompassed a full HMI concept. Hence, all components or combination of components are tested in the physical context of the full HMI, which provides more valuable results than testing a component in isolation, as is necessary in a holistic design approach.

Research into existing HMIs

Research into existing HMI designs was needed to gain insight into specific design solutions. Colour usage, icons, auditory and haptic feedback, and research in the visibility regarding the placement of visual cues was conducted to translate the requirements into an HMI design. This yielded a holistic design in which 10 HMI components (see 1.4) cooperate in order to communicate either automation/driver responsibility, driving modes, time-budget, and/or driver state; provide transparency and to keep the driver in the loop.

Literature and expert opinions

Besides existing HMIs, existing literature (theoretical knowledge) on human-system interactions as well as expert knowledge were used in the development of the Mediator HMI.

Stakeholder workshops

Stakeholder workshops with both the scientific board, the industrial board and further invited stakeholders are intended to share and more importantly triangulate research findings. In MEDIATOR four stakeholder workshops have been organised in The Hague, Turin, Chemnitz and on-line, each with their own theme.

Next to triangulation the workshops have also been valuable in collecting missing or completing insufficient data because of COVID-19 limitations. The Chemnitz stakeholder workshop theme was HMI. While this workshop proved to be very valuable, for HMI we were also able to triangulate and retrieve data from the other workshops.

Assumptions

In the design process we have assumed that auditory signals are in the proper volume and visual cues are readily visible. Note that the initial HMI design is equipped with both light and sound sensors in the vehicle, to continuously adapt HMI signals to their environment. This adaptability could not be materialised in any of the simulators or vehicles. In one on-road trial the visibility of specific lighting proved to be insufficient in on-road testing, while it was more than adequate when the vehicle was still in the laboratory. Because we consider that a prototyping fault and not an intended design fault, we have adapted the vehicle accordingly in between trials.

1.4. Overview of the Mediator HMI

The aim of this document is to propose design recommendations for the development of HMIs for vehicles with autonomous driving capability, and to construct the framing rules and regulations. Mediator's own HMI is our interpretation on how to apply our HMI design guidelines, interpret its research findings, and iterate the design process. While in each Chapter the HMI features that are relevant to that specific knowledge gap are being described, an overall description of the full HMI design is provided here.

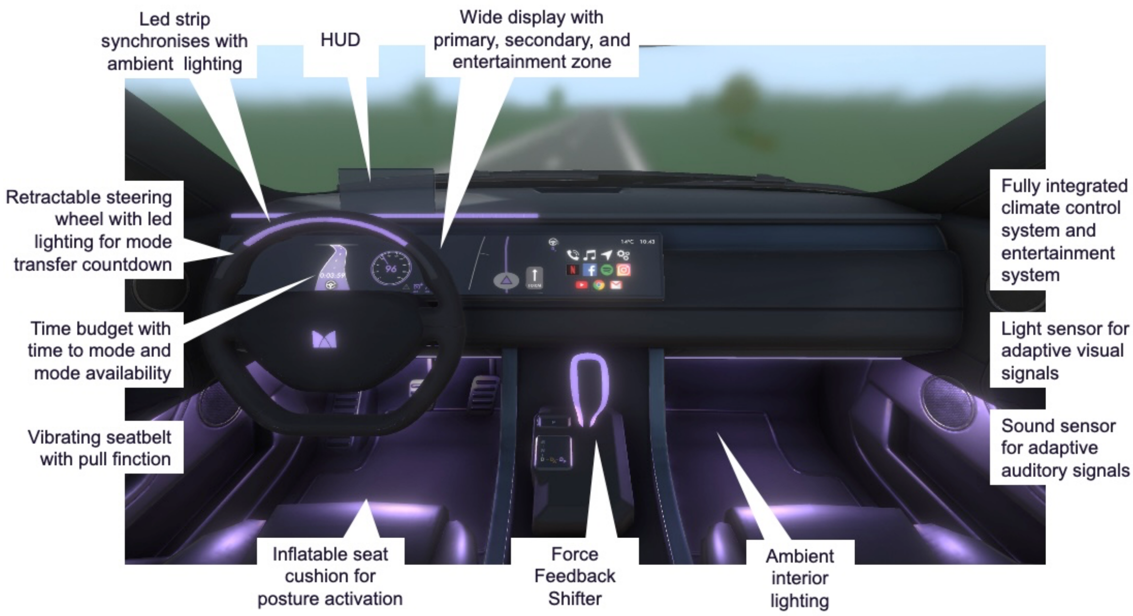


Figure 3 overview of the HMI components

1.4.1. HMI generic interaction ritual explained

The generic transfer ritual, rather interaction ritual because other interactions like fatigue and distraction mitigation follow the same flow, is depicted in Section 1.1 in the Mediator system and in more detail in Figure 4.

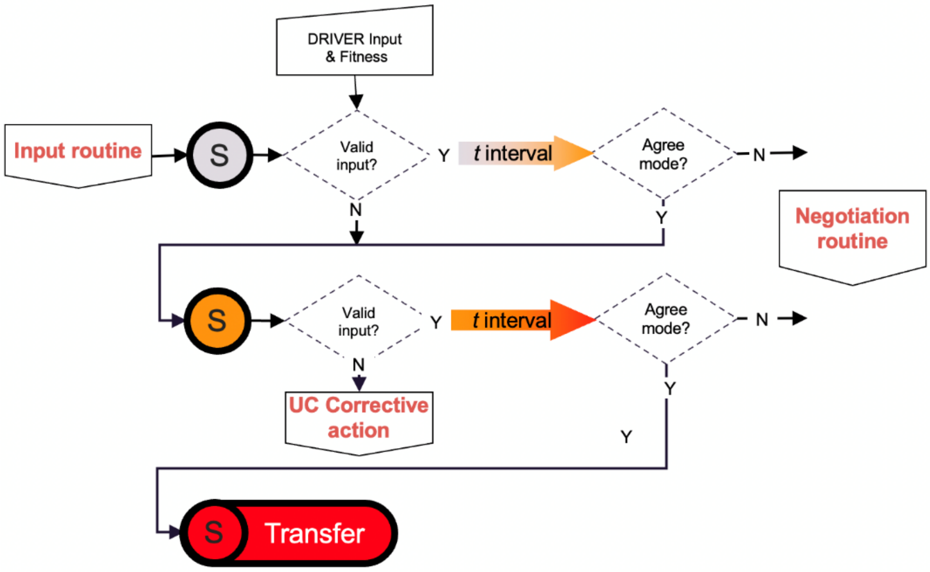


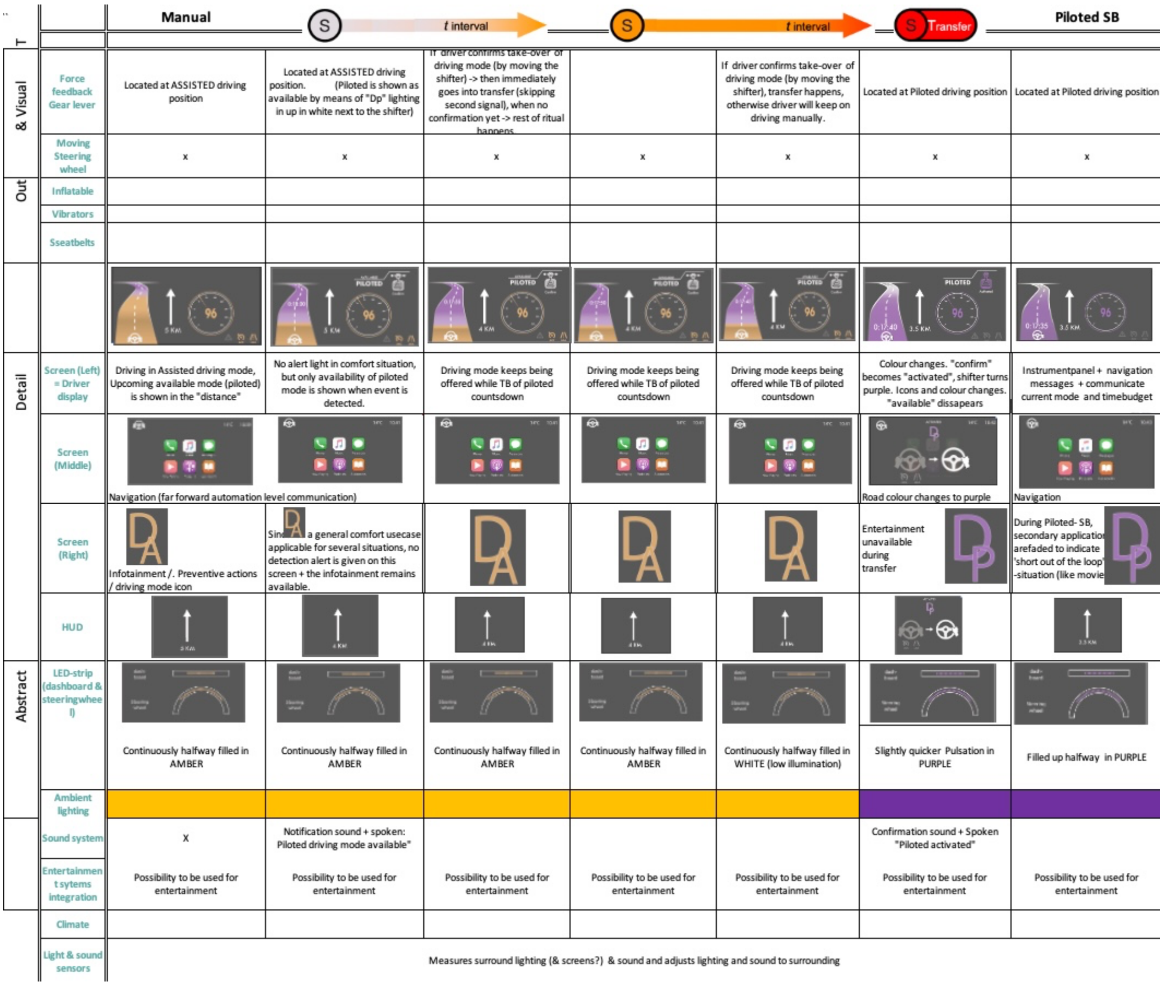
Figure 4 Generic interaction ritual with three signals, time-intervals in between, and control transfer.

The ritual is evoked by either DL or driver input. During both time intervals driver fitness is monitored. In case of driver unfitness, the time interval towards the next signal is shortened and depending on the use-case intensified. In case of continued driver unfitness, the UC Corrective Action is activated. The driver can always interrupt the ritual e.g., by immediately changing the driving mode. In case the driver is deemed fit but disagrees with the by DL proposed driving mode, the negotiation routine is activated.

1.4.2. HMI components' behaviour

The iterative design cycle resulted in specified guidelines for the design of the HMI components, the behaviour per component, and the behaviour between components. The behaviour of components has been specified in tables in which for each use-case the behaviour of each HMI component is specified in seven conditions; the situation before, the Interaction ritual i.e., three signals with two time-intervals in between, and the situation after. These overview tables, because they also visualize the interaction between components at any given time, have proven to be crucial to design the HMI holistically. A sample of the table for a representative use-case is depicted in Figure 5.

For the larger studies, different compositions of the complete HMI were designed and built in in terms of integrated components with respect to the intended study i.e., knowledge gap. One full HMI was built in the Human Factors (HF) vehicle that was used for on-road tests in both Italy and Sweden (see (Borowsky et al., 2023a).



T		Manual	S	*t* interval	S	*t* interval	S Transfer	Piloted SB
Out & Visual	Force feedback Gear lever	Located at ASSISTED driving position	Located at ASSISTED driving position. (Piloted is shown as available by means of "Dp" lighting in up in white next to the shifter)	If driver confirms take-over of driving mode (by moving the shifter) -> then immediately goes into transfer (skipping second signal), when no confirmation yet -> rest of ritual happens		If driver confirms take-over of driving mode (by moving the shifter), transfer happens, otherwise driver will keep on driving manually.	Located at Piloted driving position	Located at Piloted driving position
	Moving Steering wheel	x	x	x	x	x	x	x
	Inflatable							
	Vibrators							
	Sseatbelts							
Detail		5 KM 96	PILOTED 5 KM 96	PILOTED 4 KM 96	PILOTED 4 KM 96	PILOTED 4 KM 96	PILOTED 0:17:40 3.5 KM 96	0:17:35 3.5 KM 96
	Screen (Left) = Driver display	Driving in Assisted driving mode, Upcoming available mode (piloted) is shown in the "distance"	No alert light in comfort situation, but only availability of piloted mode is shown when event is detected.	Driving mode keeps being offered while TB of piloted countsdown	Driving mode keeps being offered while TB of piloted countsdown	Driving mode keeps being offered while TB of piloted countsdown	Colour changes. "confirm" becomes "activated", shifter turns purple. Icons and colour changes. "available" dissapears	Instrumentpanel + navigation messages + communicate current mode and timebudget
	Screen (Middle)	Navigation (far forward automation level communication)					Road colour changes to purple	Navigation
	Screen (Right)	Infotainment /. Preventive actions / driving mode icon	Since a general comfort usecase applicable for several situations, no detection alert is given on this screen + the infotainment remains available.				Entertainment unavailable during transfer	During Piloted- SB, secondary application arefaded to indicate 'short out of the loop' -situation (like movie
	HUD	5 KM	4 KM					
Abstract	LED-strip (dashboard & steeringwheel)	Continuously halfway filled in AMBER	Continuously halfway filled in AMBER	Continuously halfway filled in AMBER	Continuously halfway filled in AMBER	Continuously halfway filled in WHITE (low illumination)	Slightly quicker Pulsation in PURPLE	Filled up halfway in PURPLE
	Ambient lighting							
	Sound system	X	Notification sound + spoken: Piloted driving mode available"				Confirmation sound + Spoken "Piloted activated"	
	Entertainment sytems integration	Possibility to be used for entertainment	Possibility to be used for entertainment	Possibility to be used for entertainment	Possibility to be used for entertainment	Possibility to be used for entertainment	Possibility to be used for entertainment	Possibility to be used for entertainment
	Climate							
	Light & sound sensors	Measures surround lighting (& screens?) & sound and adjusts lighting and sound to surrounding						

Figure 5 Example of HMI components behaviour table HMI components are listed on the left, while seven columns show the behaviour of ach HMI component before, throughout, and after the ritual.

1.4.3. Mediator's ambient mode awareness colours

The human's photopic range was considered for the selection of colours that are used for the driving modes across HMI components to create one coherent information system.

- **Yellow/Amber** (used for Assisted driving mode) has one of the highest luminosities, attracting the attention of the driver. This is of importance to keep the driver actively involved in the driving task (Continuous Monitoring).
- **Purple/Magenta** (used for Piloted driving modes) has a lower luminosity, attracting less attention and so indicating less involvement of the driver. Furthermore, purple is a colour generally associated with luxury i.e., comfort.
- While in some trials white lighting was applied in Manual driving mode, in the final design manual driving is not supported by ambient lighting.
- Colours that already have meaning i.e., Learned Affordances, such as red and green have been ruled out.
- Blue, although considered in early design iterations, was ruled out because of its negative paling effect on vehicle occupants.

2. Transition of control

Well-designed transitions between different levels of automation are of utmost importance in establishing a safe interaction between the driver and the system (Lu, Happee, Cabrall, Kyriakidis, & de Winter, 2016). Especially the transition from a high level of automation to a lower level of automation, i.e., in which the driver must be in charge again, proposes a challenge. In higher levels of automation, the driver might become involved in other non-driving related activities which might propose difficulties in drawing the driver into the driving task again. On the other hand, going from manual driving to higher levels of automation can involve confusion on when the car is capable to takeover (parts) of the driving task. In this chapter we discuss HMI concepts that deal with preparing the driver for an upcoming takeover, informing the driver on the upcoming takeover, the timing of the takeover as well as on the urgency of the takeover.

2.1. Transfer ritual

Based on the literature research as well as a user questionnaire study among 26 Tesla autopilot users, a ‘journey map’ reflecting the takeover experience was created. The journey map gives an overview of the (required) actions and status of the vehicle and driver over time. Based on this ‘journey map’ a first HMI concept was designed that communicated control transitions. The concept consists of communication through light strip signals (located at both A-pillars) in combination with a head-up display.

Automation-levels, and transfers were communicated by distinct light ‘vibes’, whereas the length of the light-strips indicated the time that is left until takeover.

Based on a first user test, with 6 participants by means of a prototype setup, the concept has been redesigned to cope with the experienced issues, relating to the information on the takeover. One important issue was that participants missed information on what was exactly expected from them after the wakeup call. The mode-change through light signals from wake-up to takeover (by a LED-bar countdown) was unclear and participants indicated to prefer an indication of the time that was left before takeover was due instead of only an indication bar. Also, the confirmation of a successful handover would have been appreciated (see E.D. van Grondelle et al. (2021)).

In the second concept, the design has been optimized with an additional stage with seat-vibration and HUD messages to establish more guidance (preparation stage) until the actual takeover finds place. Also, the light strips changed colour to increase the feeling of urgency and single tone audio reminders were used in case the driver was not alarmed by the wake-up call.

Based on the knowledge following from the evaluations of these first concepts an updated journey-map was created (see Appendix A). Next, the Mediator transfer ritual has been further developed, accustomed to the different types of takeovers and fitted into the integral Mediator HMI. This has been done with the aim to address all use-cases in which a takeover to higher and lower levels of automation is required, due to a change in external circumstances, driver fitness or automation fitness. While the template of this transfer ritual and its components are fixed, the values of each component vary. All transfer rituals have been based on the developed template ritual as shown in

Figure 1 and Figure 4. In

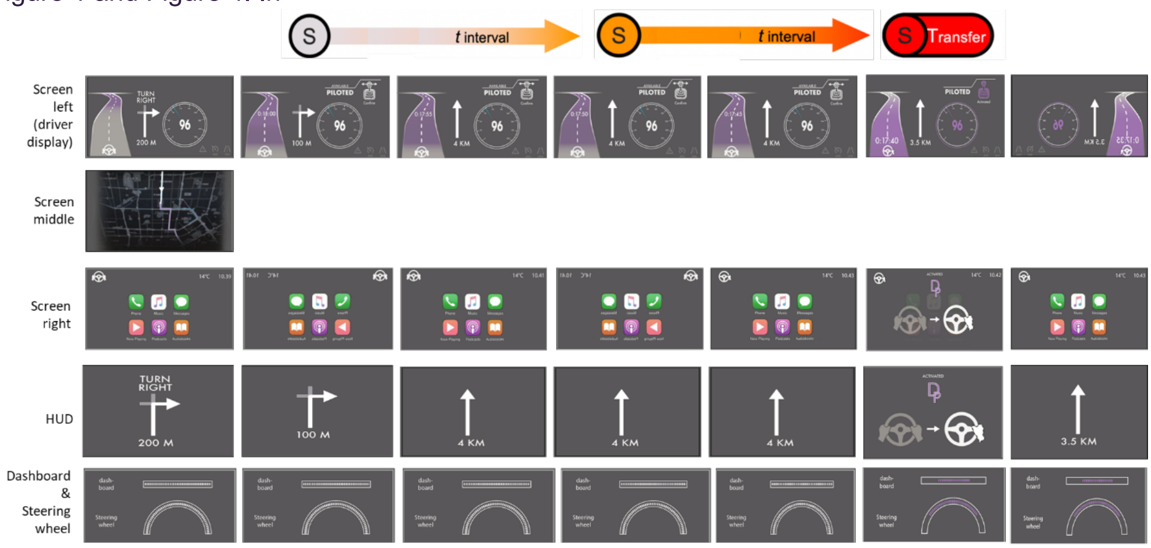


Figure 6, as an example, the ritual is depicted for use-case 3b, and how the HMI display component.

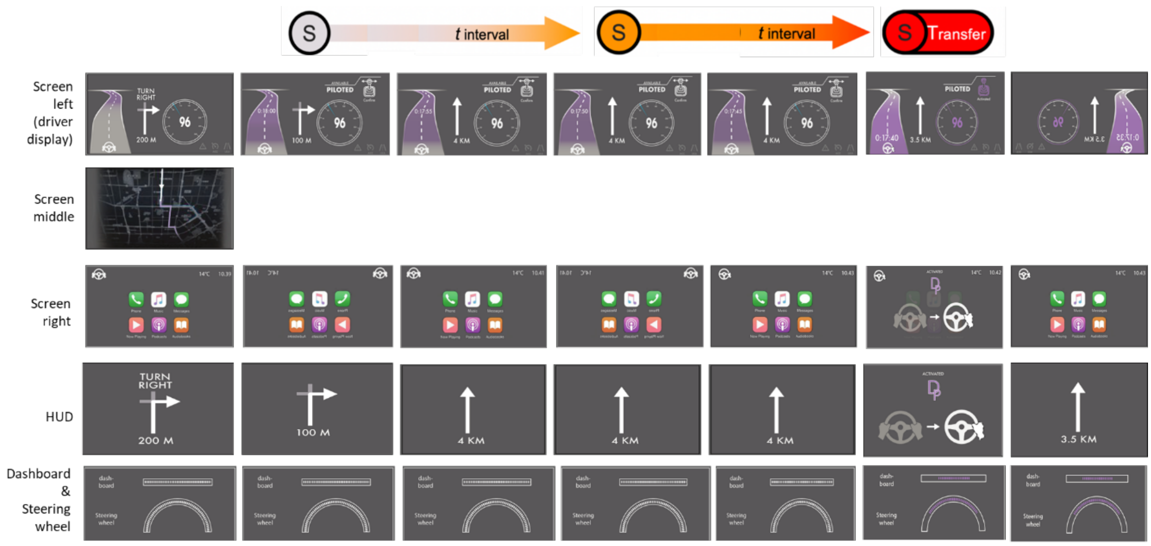


Figure 6 HMI display components for the Mediator transfer ritual for use-case 3b: The Mediator system detects an event, such as receiving a text message or an upcoming traffic jam, from which it concludes that the driver comfort could be improved. The system reacts by suggesting a takeover to automation.

Evaluations (see (Borowsky et al., 2023a, 2023b) in general, indicated that takeovers, communicated by the Mediator system, were experienced as safe, easy to follow contained timely warnings. However, some participants found the urgency level of the takeover requests as well as the reason why a takeover was proposed not always clear. More information should be provided to increase transparency of the system. Results also indicated that timing of warnings, especially related to retaking control over de driving task should be adaptable to driver's preferences since some drivers thought the succession of signals took too long. Please note that whereas the transfer-ritual and its information-steps are fixed throughout all use-cases (see 2.1), timings are dynamic and were dependent on the specific use-case. It also appeared that whereas participants were in favour of several automation levels when experiencing the three Mediator automation levels (see Figure 2), some of them were concerned about the risk of mixing up levels if people are not aware of what the different levels exactly mean. This would ask, especially with unexperienced users, for more information when starting to use the driving-system.

Participants also indicated that confusion during takeovers arose when icons were too abstract (and/or unknown). This was the case for the steering-wheel icon with one hand on the steering wheel indicating that only monitoring is required from the driver (see Figure 6, 6th column, 4th and 5th row). It was also indicated that, to feel secure when handing over control to the driving-system, the HMI should make clear of and/or when safe automation is available. Moreover, some participants indicated that they received the suggestion to switch to automation (whenever a WhatsApp/text message arrived) as too often.

While in Figure 6 only visual components are depicted, also other types of signals (auditory and haptic) as well as multi-modal signals were applied, depending on the urgency and criticality of the message.

The results from the Italian on-road study showed for urgent situations that people appreciated the most alerting multi-modal warnings: acoustic feedback, combined with haptic feedback (in this case provided by a pull-back/vibration seatbelt). A quicker HMI escalation with lower latency times would be preferred to make an alert warning sufficiently distinct from non-alerted warnings (such as: automation available). Specific takeover rituals concerning driver fitness are discussed in Chapter 4.

2.2. LEDs in steering wheel

In earlier design concepts and trials (E.D. van Grondelle et al., 2021), when led strips for signalling mode transfers were mounted in the A-pillar, their function was not fully understood by participants. Furthermore, the mode change through light signals from wakeup to takeover (the LED bar count-down) was not clear, even though led strips started blinking which conveyed the urgency of the takeover (overall the urgency of the takeover was rated with a 3.7 on a scale of 0 to 5).

In a study by Muthumani and Wang (2022) two HMI versions (HMI-1 and HMI-2) were compared with a basic HMI in a driving simulator experiment with 24 participants. In the experiment critical (unplanned) as well as non-critical (planned) transitions were presented to distracted (by a game on a touch display) participants. Transitions were between an assisted mode and a piloted mode. All three HMI variants consisted of visual icons, sounds and voice messages as well as seat belt vibrations. HMI-1 and HMI-2 consisted of additional visual cues; HMI-1 had 33 LEDs positioned on the steering wheel, HMI-2 had an array of 20 LEDs mounted on the windshield. The light patterns in HMI-1 and HMI-2 were differentiated between the type of transfer. In planned transitions, LEDs switch off one-by-one in with clock-ticking sound. In an unplanned transition LEDs started to pulsate in red.

Findings based on subjective evaluations of the participants indicated that HMI-1 with LEDs on the steering wheel received the most positive ratings concerning its design and usability. HMI-1 received the highest system usability score (SUS) is well as the highest desirability score (defined by six rating-categories) compared to HMI-2 and the basic HMI. These differences were however not statistically significant. However, the HMI-1 was by most participants (67%) ranked as the most favourable option.

Implemented in the Mediator system the LED-strips in the steering wheel were appreciated by participants since it effectively communicates with the driver without requiring glances away from the road. However, the message conveyed by the LEDs was sometimes hard to understand because it was experienced as too abstract. One has to learn first what the different colours mean.

Figure 7 HMI –1 (left), HMI-2 (middle) and the basic HMI (right) showing activate Assisted mode.

Figure 8 HMI –1 (left), HMI-2 (middle) showing active Piloted mode and HMI-1 (right) showing unplanned takeover request initiation with pulsating red.

2.3. HMI design guidelines for Transition of Control

Based on the evaluations of the transfer of control concepts, the proposed designs with LEDs on the steering wheel as well as on the windshield the following HMI recommendations are defined:

- An HMI should have a basic ritual for all changes and transfers. The template is fixed but the values of each component vary.
- Fitness of the driver, and of the driving system, should be continuously communicated.
- Personal adaptation of warning-timings in takeovers should be possible.
- Latencies between a signal and driver response should be optimized in relation to urgency and human reaction times / expectations.
- The intentions of the vehicle and the reasons for a takeover during automated driving should be clearly communicated to the driver.
- When a transfer to manual control is required, an HMI should support the driver in preparing for takeover. For example, after the ‘wake-up call’ the driver should remain attentive before the actual takeover finds place.
- In case the driver must regain control and the urgency level is high, the takeover request should be communicated by means of multi-modal intrusive signals.
- Apply a visual countdown instead of a constant or single-frequency signal, to indicate a takeover procedure.
- A visual countdown, through led or otherwise, must be positioned in the primary sightline of the driver i.e., on the steering wheel.

- Use colour codes with a dynamic pattern for request messages such as ‘automation available’, ‘activating automation’, and ‘automated driving is activated’ (see also Section 3.2).
- Use distinct colour codes to convey the vehicle mode or level related information (see also Section 3.2).
- A planned takeover, signalled by a visual countdown, must be supported by additional signals, such as seat-vibration, and textual or auditory messages to guide users through the actual take over.

3. Transparency & information overload

In highly automated driving systems, in which the system and the driver switch control, lies a huge challenge for the HMI to provide mode awareness as well as supporting appropriate system-trust. A great risk of mode confusion is that drivers misjudge their own tasks and responsibilities (Tinga, Cleij, Jansen, van der Kint, & van Nes, 2022). One way to establish mode awareness, is to make the system transparent. During automated driving, including an imminent takeover, a transparent HMI should stimulate mode awareness, the understanding of the driving mode and the driver's responsibilities. This is an important requirement for enabling the driver to sufficiently supervise the environment as well as being able to safely regulate the uptake and disengagement in Non Driving Related Activities (NDRAs) (Tinga et al., 2022). Besides avoiding mode confusion and automation surprises, transparent communication facilitates appropriate trust and reliance (Carsten & Martens, 2019).

Transparency means that the system should provide sufficient and clear information to the driver about the functioning of the system (E.D. van Grondelle et al., 2021). This way, a driver can understand the system (why does the system what at which moment?) and anticipate future actions. On the other hand, drivers should not experience an information overload that reduces driver comfort and decreases the ability to perceive and process new information. An HMI should be designed in such a way that this delicate trade-off between transparency and information-overload is optimally balanced in all situations. This chapter discusses Mediator HMI concepts that aim to establish this balance.

3.1. Communicating automation status and/or desired driving task

The driver should continuously be aware of his/her responsibilities and should be able to choose their NDRAs accordingly. From the literature and interviews with experts and (potential) users it therefore became clear that the current automation mode should be communicated to the driver at all time (E.D. van Grondelle et al., 2021). In a couple of experiments (see E.D. van Grondelle et al. (2021)), it was investigated whether people prefer to be informed on the automation level (in this case Driver Standby or Time to Sleep) or on the specific corresponding driving tasks that are required and/or allowed. For these experiments two concepts were compared against a baseline concept. The first concept (see Figure 9) showed emoticons in the middle off the dashboard indicating the reliability level (Automation Reliability) for the current automation level (left) as well as for the upcoming automation level (right). These levels were also coupled to specific colours of the icons (range from the lowest to the highest reliability level: red, orange, bright green, and dark green).

The second HMI concept (see Figure 10) showed in the middle of the dashboard icons communicating the desired driver task (Desired Task). These icons were highlighted in the same colours as used for the other concept in which automation 'fitness' was showed.

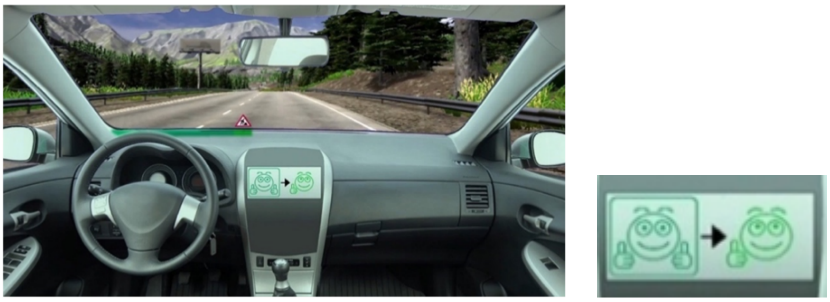


Figure 9 HMI-concept showing automation 'fitness'.

Figure 10 HMI concept showing 'desired driver task'.

In both concepts also anticipatory information could be shown, i.e., the time left in current automation level/time to next level was communicated. In the first concept this was done by a LED strip at the bottom of the windshield of which the colour and the length corresponded to the time left in the current level (the left part of the LED strip) and the time to next level (the right part of the LED strip). For the second HMI concept time in current level/time to next level was communicated by the colour in which the icon was highlighted. The highlighted area 'depleted' upwards or downwards depending on the time budget.

In addition, in the first concept ambient light in the car was simulated by overlaying the interior of the car with a transparent layer in the colour corresponding to the current reliability level. The light intensity was high when there was a lot of time left in the current automation and decreased with the decreasing time left. In the second concept, the ambient light effect/colour was similar to the one in the first concept, but here the time left was communicated through the radius of the light instead of through the intensity of the light.

Results of the statistical analyses tested the effect of Information focus (Automation Reliability versus Desired Task) and Anticipatory information (Base versus Anticipatory) and the interaction between the two on correct and incorrect statements in total and on the three levels of situation awareness: perception, comprehension, and projection.

The results, based on a think-aloud procedure with 16 participants, indicated that people understood the concept that communicated on the automation status better compared to concept that communicated on the desired driver task. People preferred concepts in which an ambience is created that nudges drivers in what to do instead of concepts that present too much detailed information on desired tasks. On the other hand, especially when people are still learning about the automation levels and corresponding responsibilities, additional information can potentially be presented through easily interpretable icons. Yet, for icons communicating the allowed tasks it appeared that some knowledge of autonomous cars and/or more information on contexts would be necessary for participants to interpret the icon's meaning and intended task.

It was also demonstrated that communicating time budgets supported drivers in understanding what will happen in the future and that it could assist in planning NDRTs. Information on time left in current mode was also appreciated by people. When a change in automation mode will occur, drivers additionally appreciate to know the reason for this change. The relatively high number of correct statements (77.19%) by the participants, while they received little to no information at the beginning, indicates that the HMI functioned intuitively. This suggests that the current design choices to obtain low information processing load, where ambient light effects are combined with icons and bar-like visuals, seemed to be easily interpreted. Ambient lighting and time-budget will be more specifically discussed in the next two Sections.

3.2. Ambient lighting

As was already shown in the previous section ambient lighting with colour coding (see 1.4) related to the automation level, can add to the situational awareness of AV drivers and may be an effective way to inform people on their responsibilities in a non-intrusive way. The remainder of the project further elaborates the concept of ambient lighting. In a study by (Tinga et al., 2023) the concept has been further optimized based on expert sessions and focus-group sessions. In the final phase, the HMI design was evaluated, and improved using virtual reality and the RITE (Rapid Iterative Testing and Evaluation) method with 18 participants (see Figure 11). The different consecutive HMI designs were evaluated by showing the four different modes (manual, continuous mediation, driver standby and time to sleep) in VR to participants. The think-aloud-method, questionnaires and semi-structured interviews were used to gain insight into how the HMI design was experienced and understood by participants. The HMI that resulted from this RITE project contained, in addition to the ambient lighting, the following elements:

- LED bar on steering wheel.
- Rectangular display implemented in the dashboard, consisting of three sections (from left to right): 1) one section straight in front of the driver (showing time in current driving mode and time to next driving mode; 2) one next to the steering wheel (showing navigation in colours of current and upcoming driving mode; and 3) one in line with the centre console (dedicated to infotainment).
- Shifter, showing by its colour and position the current automation mode.

Findings from this study indicated that this HMI is comprehended well, with a relatively low task load, and with a good experienced system usability. Yet, part of the participants indicated that they were in doubt whether they would understand clearly what would be expected of them as a driver, since the ambience doesn't specifically tell the driver what to do. Especially when people are still learning the meaning of the information presented by the HMI, it might be the case that drivers not fully understand what actions are expected from them based on only ambient lighting. A solution would be to provide more specific additional information to the ambience, for example, through well-known or clear icons.

Figure 11 The HMI design in the four different modes: the 'Manual' (M) mode in the upper left picture, 'Continuous Mediation' (CM) in the upper right picture, 'Standby' (SB) in the lower left picture and 'Time-to-Sleep' (TtS) in the lower right picture.

In the following on-road evaluations as well as the simulator evaluation studies of the Mediator driving system also ambient lighting with distinct colour schemes for different automation levels was applied. LED strips were installed on the steering wheel, on the dashboard and inside to the cabin. The colour scheme used was grey/white for manual driving mode, yellow/amber for assisted driving mode (Continuous Mediation) and bright purple/magenta for piloting (Driver Standby) and dark purple/magenta for piloting (Time to Sleep). In case of an urgent takeover, the LEDs on the steering wheel turned red. The human photopic range was considered for selecting the colours, without interfering with existing associated colour meanings.

Figure 12 Ambient lighting in Technology Integration Prototype vehicle that was used for on-road evaluation of Mediator system

Based on the simulator study performed in Germany (see Borowsky et al. (2023b)) as well as in the on road studies performed in Italy (see Borowsky et al. (2023a)) it appeared that people in general comprehend and appreciate the concept of ambient colour coding of automation levels. Participants thought that the colour schemes contributed to the clarity of the system, making it easier to keep track of the current automation mode. It was also stated that the colours were selected wisely (no confusion with traffic lights or blue light of emergency vehicles) and that they were perfectly visible in the periphery and helped to identify the current driving mode easily. A few participants indicated that they did not always understand the colours and that they would prefer more contrasting colours.

In the Italian on-road study participants indicated that the ambient lighting and colours were not always clearly visible under specific exterior conditions.

3.3. Time budget

The concept of time budget has been further developed. Besides the depletion of LED-bars as well and changing colour intensities (see 3.1) for the final evaluations a widget of the road on the driver display is shown. This widget informs the driver of the current driving mode, as well as its 'time-budget' (time to next driving mode) and the upcoming driving mode (available time) using colour, icons, and timers (Figure 5). The colours are identical to the colours used in the ambient lighting. No time budget is shown during manual driving indicating that it's always available (See Figure 13)

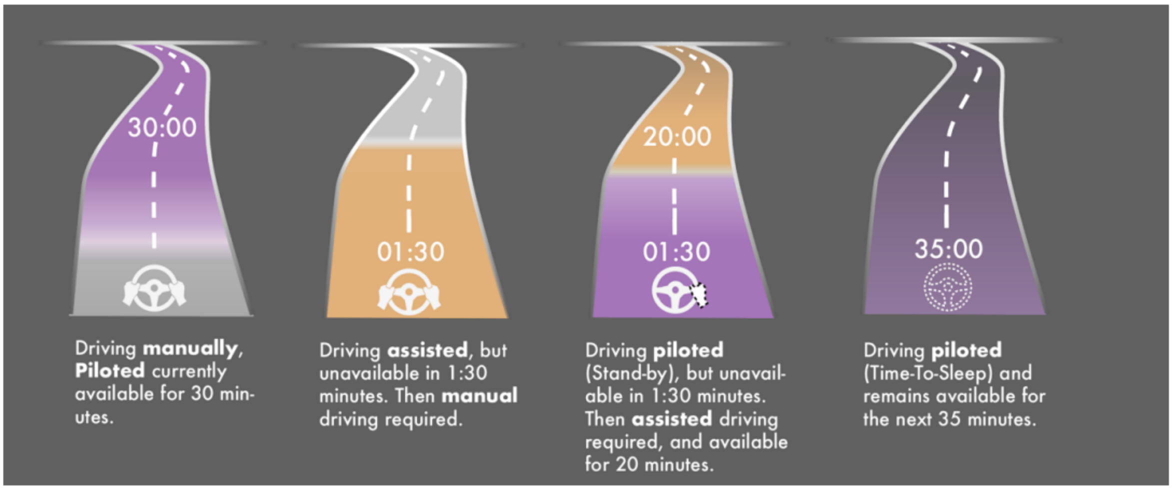


Figure 13 Examples of possible Time-Budget scenarios.

Based on the tests and evaluations of the time-budget concept it can be concluded that continuously communicating time budgets supported drivers in understanding what will happen in the future and that it could assist in planning NDRTs (See (Borowsky et al., 2023a, 2023b; E.D. van Grondelle et al., 2021)). Furthermore, while not all people could correctly explain the meaning of the parts of the road, it seemed that driver's understanding increased with extensive experience based on the results of the simulator study in Germany (Borowsky et al. (2023b)).

3.4. HMI design guidelines for Transparency and information overload

Based on the findings, it can be concluded that:

- The HMI must communicate the current driving-mode continuously and in a holistic way. This can be achieved, for example, through ambient lighting (see 3.2).
- The HMI should communicate the time left in current mode/time to next mode continuously while clearly signifying the current mode. This can, for example, be attained through communicating the time in a number, or, through a LED bar depleting over time with decreasing time in the mode.
- When the current mode will change to another mode the HMI should communicate the reason for this change in advance. This requirement can be attained by for example using icons for an event that will occur in the environment, for example indicating that roadworks ahead, or that the car will leave the city.
- The HMI should nudge and/or inform the driver about what to do. Especially drivers that have not much experience with the driving system should get explicit information (for example, icons or spoken text) next to non-intrusive implicit information (for example, ambient lighting).
- Design ambient awareness with different colour codes to continuously inform the driver in a non-intrusive way of the current automation level.
- Ambient lighting should, especially with inexperienced drivers, be accompanied by other types of information (for example visual/auditive information) on automation levels/modes.
- Continuously communicate the time budgets in the current mode as well as, the upcoming driving mode.
- The symbols and colours of the different driving levels shown in the time-budget widget should be consistently used throughout the ambient communication of the different driving levels (such as ambient lighting).

4. Keeping the driver in the loop

Partial automated driving requires the driver to continuously monitor the driving situation. Successful monitoring of the driving presents two challenges: 1. Mode awareness should be attained, and mode confusion and mode errors should be prevented 2. Vigilance should be maintained, and vigilance deterioration should be prevented. Mode awareness and situational awareness are discussed in Chapter 3. In this chapter we discuss HMI concepts aimed at preventing vigilance deterioration. Vigilance deterioration (driver 'unfitness') can be caused by task overload (active fatigue), task underload (passive fatigue), sleepiness as well as distraction. Especially in continuous mediation situations, it is important to keep or improve driver fitness to maintain a safe driving situation. Therefore, within the MEDIATOR project corrective as well as preventive HMI concepts have been applied that address fatigue (task underload & sleepiness) as well as distraction. Preventive measures are measures that that are aimed at maintaining driver fitness, whereas corrective measures are applied as a response to deteriorated driver fitness (distraction/sleepiness).

4.1. Non-driving related task (NDRTs)

Providing a preventive NDRT in case of continuous mediation may support maintaining situational awareness since disengagement from driving-related activities for prolonged durations, can cause passive fatigue, particularly when drivers are focused on the road and monitor the automation (Naujoks, Purucker, & Neukum, 2016).

In one Mediator evaluation simulator study (see (Borowsky et al., 2023b)) with 24 participants a non-driving related trivia task was used as a preventive measure for fatigue due to underload during assisted driving. In this Israeli simulator study, an auditory and visual Trivia game as used to prevent task underload (passive fatigue). The invitation to play the game appeared visually on the infotainment display (see Figure 14). It was either independent of fatigue, in which case it was considered preventive, or it could follow a subjective indication of fatigue by the driver, i.e., the Karolinska Sleepiness Scale (Akerstedt & Gillberg, 1990) reached a certain threshold. In the latter case it was considered a corrective measure. Each time a driver accepted the suggestion to play the trivia game, questions appeared visually as well as via the speakers. Each question included four answers of which the driver could choose one as the correct answer on the display. In case fatigue was detected an escalation strategy was applied (see 4.2), consisting of three consecutive signals, according to the Mediator generic ritual (see 2.1). Although, fatigue-related differences were not found between the Trivia- and non-Trivia groups, the Trivia game appeared to support maintaining situational awareness (based on eye tracker data). This effect remained over time (across two driving sessions).

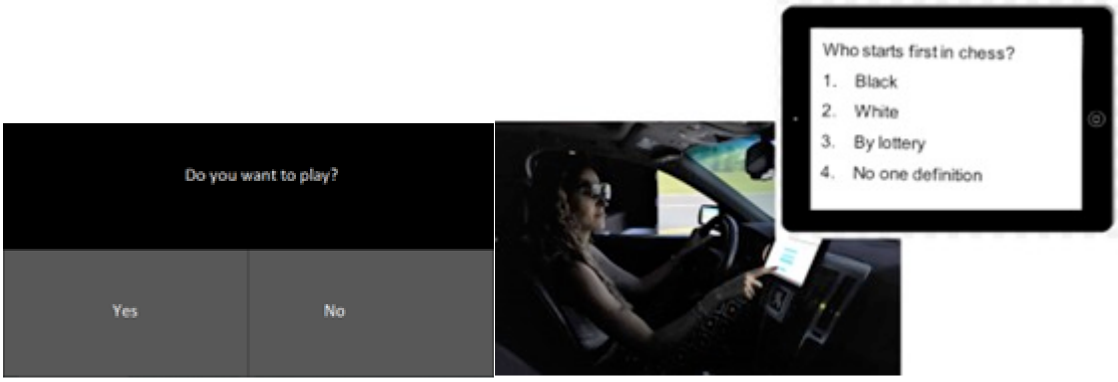


Figure 14 An HMI preventive/corrective mediation; The invitation to play Trivia (on the left) and an example of a question.

4.2. Distraction / fatigue warnings

In three (two on-road and one simulator) Mediator evaluation studies (see (Borowsky et al., 2023a, 2023b) HMI warning concepts in case of distraction or fatigue have been tested. These concepts are based on the Mediator generic transfer ritual, as described in Sections 1.1 and 2.1).

If fatigue was detected, a degraded fitness message was shown on the displays and an audio alert was triggered. In the on-road trial also a cushion in the seat was inflated to give the participant a more upright position as well as a gentle vibration in the seatbelt. The warning was escalated if needed, by a second notification accompanied by a stronger audio alert, and in case of the on-road trial an auditive message (“rest required”) as well as a seatbelt vibration. If this did not help, an emergency takeover was triggered, and the LEDs started pulsating in red. A similar procedure was carried out if distraction was detected, but with a corresponding distraction message instead of a degraded fitness message. See the different icons in Figure 15 and Figure 16. In case a suitable (higher) level of automation was available in case of distraction, the Mediator system suggested the driver to switch to the concerning driving mode. Note that distraction warnings were inhibited in piloted mode. Figure 17 shows the ritual of a suggested mode switch in case of distraction.

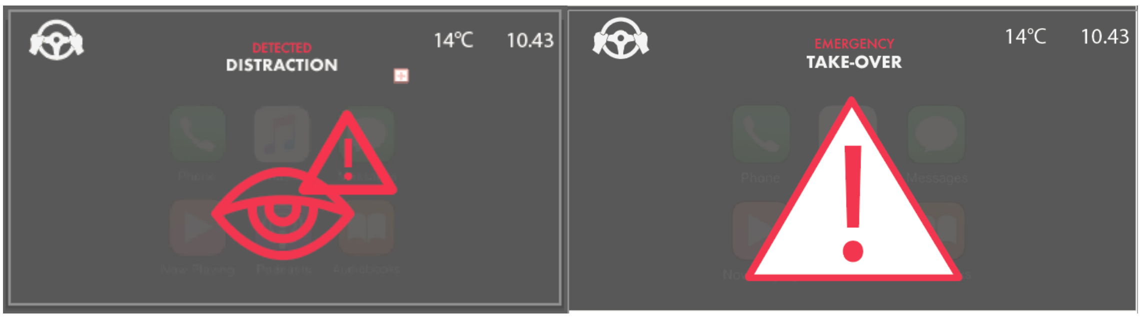


Figure 15 Visual warning messages shown to distracted participants at levels 1 (left) and 3 (right).

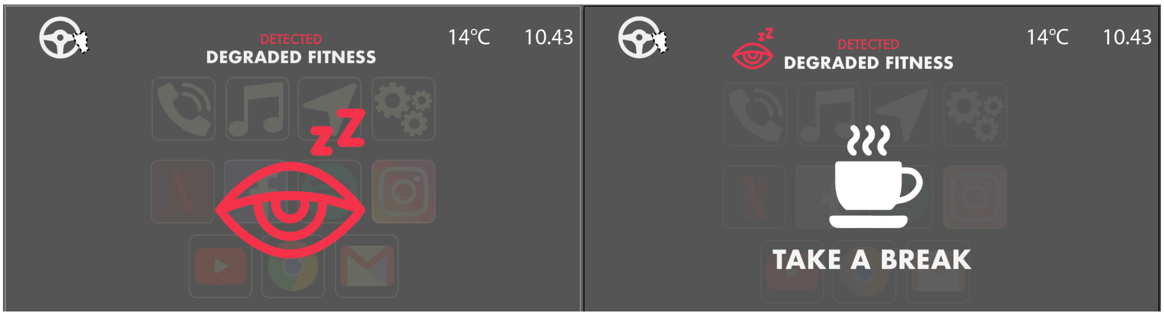


Figure 16 Visual warning messages shown to fatigued participants at levels 1 (left) and 2 (right).

Figure 17 Sequence of displays for suggested mode switch by the Mediator system in case of distraction. To elicit the urgency of the situation the roadsides are turned red.

Results from the study by Borowsky et al. (2023a), Chapter 3, indicated that the suggested mode switch with alert messages somewhat reduced task-related fatigue but not sleep-related fatigue.

The distraction warnings were in general appreciated but the applied icons, depicting what is expected from the driver, appeared not always to be clear concerning their exact meaning. Participants indicated that in case of hand-over due to distraction, the system did not give direct suggestions on what (possible) behaviours are expected from the driver. However, the results also indicated that the Mediator HMI, including distraction warnings, resulted in less distraction in assisted driving compared to a baseline HMI, with no distraction warnings.

In the Italian on-road study results indicated that the frontal display did not capture the driver's attention when the driver was distracted from (assisted) driving. Other multimodal signals attracted the driver's attention.

4.3. Seatbelt-pull

Experiencing haptic feedback, for example by means of the seatbelt can, effectively redirect visual attention to time-critical events or important information in front of the driver (Gaffary & Lécuyer, 2018; Ho, Hong, & Spence, 2005; NHTSA, 2011). Therefore, this concept was introduced in the Mediator HMI. The part of the seatbelt that touches the lower part of the torso contains a seatbelt pull force that is activated in case of an emergency/unplanned takeovers. Evaluations showed that the haptic feedback of the seatbelt is effective. However, some participants considered it a bit annoying since they experienced the seatbelt-pull as too strong.

4.4. HMI design guidelines for Keeping the driver in the loop

- The availability of an optional and conditional NDRT in the HMI is recommended.

Conditionally, NDRT under partially automated driving should not distract attention from the roadway and glances inside the vehicle should not be longer that two seconds and for a total of 12 seconds per task (NHTSA, 2016). Moreover, mental demands by a NDRT should not impair the driver’s ability to take over whenever it is necessary.

- Alert messages should be designed according to a generic (see Chapter 2) escalation ritual.
- Alert messages should consist of multi-modal signals, such as acoustic signals, text messages, and seatbelt vibration and visual signals.
- Alert messages should be accompanied by suggestions or instructions of actions to be taken by the driver.
- Apply haptic seatbelt feedback in case of emergency or unplanned takeovers as well as in case of distraction. The force of the seatbelt feedback should be adjusted to the weight and length of the driver.

5. Negotiation conflicts

A common assumption in autonomous driving research and design projects is that the system determines the suitability of the driver to control the vehicle, based on the complexity of parameters that are either known about the driver and the driving context, or measured in real-time. In this line of thought the system decides unilaterally who has control over the vehicle, the driver, or the automation.

This disqualification of driver autonomy is in sharp contrast with the acquired status-quo, in which full driver autonomy is obtained once for a lifetime, only to be reassessed in special circumstances e.g., old age, medical reasons, or alcohol abuse. From this we deduct, and we see this confirmed in literature research, that driver autonomy is paramount for user acceptance, its success depending on its ability to facilitate driver autonomy, specifically towards chosen driving-modes. Note that disqualification of the driver also conflicts with the Mediator philosophy, which acknowledges that both driver and automation each have their own view, and perception of the driving context (Christoph et al., 2019), neither of which are binary (E.D. van Grondelle et al., 2021).

While acknowledging driver autonomy as a key element of comfort, interrelated with trust, and therefore crucial for user acceptance, implied challenges arise during the transition to higher automation levels, such as increased instances of disagreements between the driver and the automation system over whom should take control. In Mediator's HMI a negotiation routine was being developed to negotiate these disagreements, based on human negotiation styles (Shan, 2021). In the next sections the implementation of the negotiation ritual in the HMI is explained for both software (interaction flow) and hardware (a force feedback shifter).

5.1. Negotiation interventions, interaction flow

Negotiation styles were developed in which persuasive or seductive negotiation is activated, depending on whether DL's driving mode recommendation is respectively, comfort, or safety based (Shan, 2021).

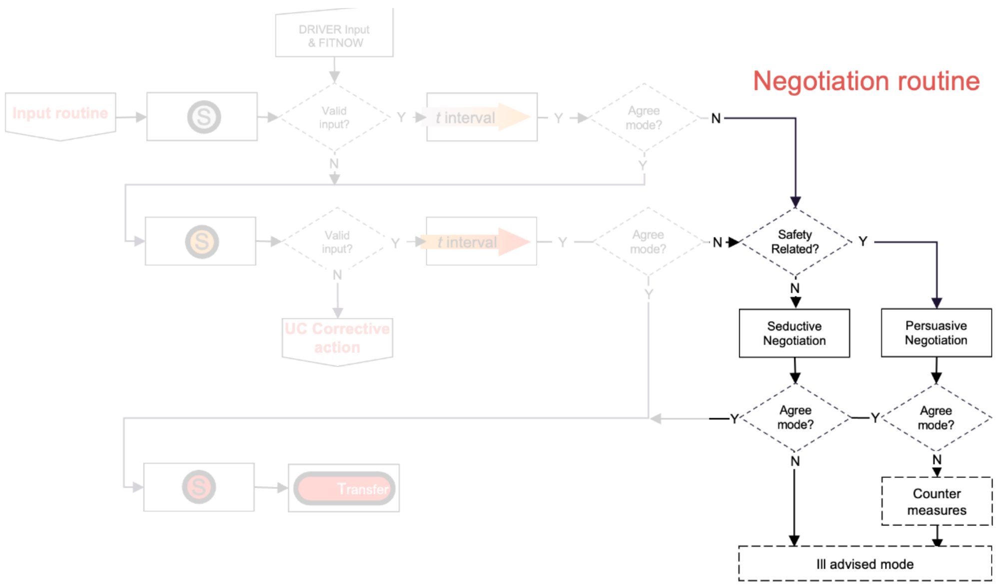


Figure 18 Generic interaction ritual with on the right side the negotiation routine.

In a persuasive negotiation mode i.e., DL proposes a higher available autonomous level for comfort reasons, driver autonomy is unchallenged. Persuasive negotiation is being employed in safety related ODDs e.g., if the driver is unfit, or to mitigate upcoming driving conditions like heavy traffic or weather. Seductive negotiation is employed in a collaborating style to effectively motivate drivers by either counter measures e.g., reducing the vehicle's performance, or increasing intrinsic and extrinsic incentives e.g., parking benefits at destination. See Figure 18.

5.2. Negotiation interventions, force feedback

A crucial HMI component in Mediator's human machine negotiation is the Force Feedback Shifter. The conventional shifter for vehicles with an automatic transmission is expanded its standard R, N and D (Reverse, neutral and Drive) with Mediator's two automated driving modes next to Drive (Figure 19*)*.As such, it complies with the design principle to facilitate intuitive learning by existing affordances (see 1.1). In D (drive) either driving mode can be selected by nudging the shifter to the right. Its force feedback mechanism provides the physical interaction with the driver in case of negotiation. The shifter blocks mode selections that are not available. Furthermore, it will resist mode selections that are discouraged by decision logic DL, making the mode selection a very conscious choice.

Figure 19 Force feedback shifter in the HF prototype vehicle, placed in the mid console behind the vehicle's original shifter and recognisable by its lighted grip.

The force feedback shifter itself was the outcome of an early design iteration in which several design concepts have been tested, framed by learned affordances. In later studies however, the shifter was evaluated differently by participants. Many participants stated that they would prefer to select driving modes on a touch screen instead. This finding may be explained by several factors:

- This may have been influenced though, by the somewhat uncomfortable positioning of the shifter in the HF prototype vehicle, behind its real shifter (Figure 19). It was installed in its intended position in an interior mock-up of the Mediator HMI, gaining more positive initial feedback (Figure 20). This could however, while intended, not be thoroughly tested with respect to Mediator's timeline.
- Another factor is that the research into existing affordances, by which the shifter was designated as the best solution, has been conducted early in one of the earlier design iterations in the project. Since then, the rise of electric cars without a conventional shifter as well as the availability of touch screens in cars, have substantially increased. Most likely, renewed research into learned affordances will favour touch screens over conventional shifters.

- From a technology standpoint, touch screens with force feedback have not yet passed automotive industry validation with respect to durability and performance. Having said that, various OEMs are considering, or already reversing to, physical switches for primary functions because of ergonomic and functionality limitations of touch screens in a moving vehicle.

Figure 20 Intended position of the Force Feedback Shifter, next to the steering wheel, in an HMI mock-up.

5.3. HMI design guidelines for Negotiation conflicts

While the original intent was to limit the research on conflicts between driver and DL to literature research, one of the earlier design iterations has been designated on designing and investigating the negotiation routine. In the larger simulator and on-road studies the routine has not been specifically implemented and tested, but in the overall studies and the stakeholder workshops we have been able to triangulate. Design recommendations that were primarily derived from the early research by design iteration, and secondarily from the larger studies and the stakeholder workshops:

- The need for, or the value of, driver autonomy is generally confirmed.
- Countermeasures that reward a driver's regular compliance with DL advertised autonomous mode like parking benefits, work better than negative countermeasures, such as reducing a vehicle's performance in terms of speed and acceleration.
- The reason for a by DL advised autonomous mode must be communicated to the driver. This contributes to the negotiation outcome and calibrates trust.

Note that, while a multi-modal negotiation routine with haptic feedback, resisting ill-suggested mode changes, seems valid. However, further research is recommended to substantiate a hard recommendation.

6. OEM design space

The automotive industry is structured by, and built on, deeply rooted emotional values of automobility (E.D. van Grondelle, 2016). While autonomous driving technology is a short-term business opportunity to create strategic advantage, in the long-term, this rationalization of automobilism poses a risk toward the aforementioned automotive merits and structure because its rational parameters do, in principle, not inspire variation. For industry acceptance though, diversification in brand identity i.e., brand specific design of the human-product interaction, and manifestation of the HMI system (behaviour, look and feel) are crucial. Brand identity i.e., the brand-specific design of the HMI is crucial for market penetration (Fiorentino et al., 2020).

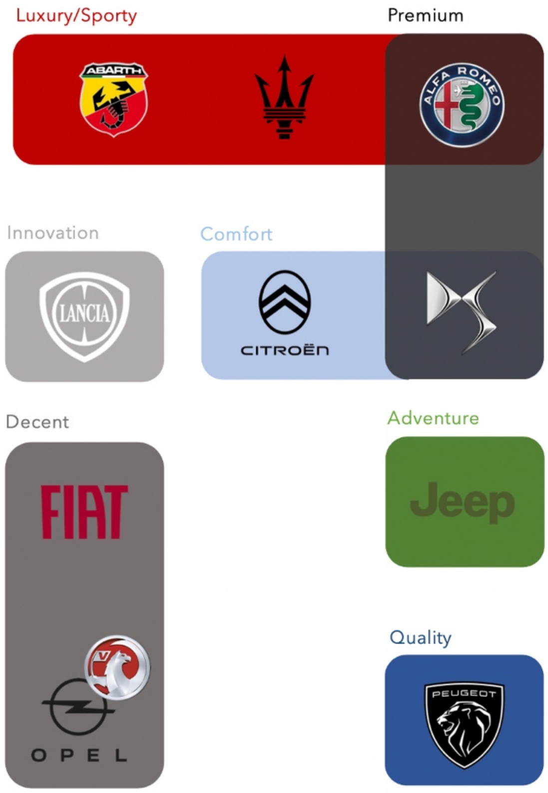


Figure 21 Consortium partner Stellantis' brand portfolio. Each brand must be able to diversify their brand experience and offer a unique proposition (from a brand portfolio strategy design exercise, Delft University).

In the MEDIATOR design process this means that we aim to identify design space i.e., applicable value ranges and variation in visual, auditory, and tactile design, rather than single values. In Figure 21 brand roles in the Stellantis' brand portfolio are being suggested. As an example, apart from graphical adaptation to brand identities, brand identity may also be expressed in e.g., different autonomous mode suggestions by the Mediator system, depending on if a brand is considered sporty or luxurious.

For this knowledge gap, the initial research plan, which included several brand-related design projects, could not be completely fulfilled because of COVID-19 restrictions, specifically at the OEM partner. However, from the regular interaction, and particularly from the stakeholder workshops that were attended by both OEMs and suppliers, we have been able to derive the following discussion and conclusions.

In principle, we see initial confirmation that design space can be facilitated as Mediator's HMI has been built in various composition of its components, as well as in how they are implemented and positioned. Depending on the aim of the study in its low-cost or high-level driving simulator, or vehicle for on-road testing, there is variation in the installed components. To some level, installations were also different in their design implementation of components. Although the complete HMI design (Figure 2) foresees in an instrument panel with a large display with three dedicated zones (Figure 10), and a head-up display, the number of displays differs per simulators or vehicle. And while in the larger studies the ambient colour scheme is adapted throughout, the number and locations of led strips vary.

Initially, the intent was to investigate the design per component or category such as visual, acoustic, or haptic. These discussions often diverted beyond brand identity towards HMI adaptability to personal preferences. The discussion on design space was kept on a more holistic level. Specifically, the ambient lighting experience i.e., implicit awareness of autonomous mode was a common subject in discussions about the design space.

The need for design space has been confirmed throughout the project from earlier studies on (Grondelle at al., 2021), as well as abundantly in the stakeholder workshops in which design experts from various OEMs and suppliers participated. The value of emotional attachment was specifically mentioned by participants in some of the studies, suggested to increase acceptability, and therefore usage and perceived safety. Outside the scope of this discussion, or rather in its extension, variation in HMI design may also adapt to drivers' personal preferences with respect to information overload and intuitive learning.

6.1. Stakeholder workshops

Mainly in the stakeholder workshops though, it was debatable what features should be regulated, and what features should be left free for OEM to communicate brand identity. What features should be regulated, what should be a guideline, what should be a standard or norm? The leading question is, what is required to ensure safety? While there is agreement on that HMI features are strongly tied to brand identity, and opinions vary on the extent of the design space, experts are unanimous in that there are limits.

While Mediator's ambient lighting solution was generally appreciated, as well as its chosen colours that are based on learned affordances, luminosity, and the meaning of the colours, it was also acknowledged that other solutions may be as viable.

The most important unanimous agreement is that any HMI features that communicate mode awareness must be consistent across brands. The meaning of signals, either visual or auditory, must be the same in all vehicles.

A final suggestion from the stakeholder workshops, with respect to the previous agreement, is that design recommendations in MEDIATOR would preferably be of the form 'make it ambient and decide on standard colours for each automation level'. How exactly it should be implemented is beyond the scope of MEDIATOR.

6.2. HMI design guidelines for OEM design space

- In the development of legislation or design recommendations, it is important to acknowledge the OEM design space, so that brand identity can be conveyed.
- The transfer of control ritual must be similar across vehicles.
- In case of mode awareness through ambient colours, colour coding must be similar across vehicles and brands. Colours cannot have another meaning from one vehicle to the next.

- Information on autonomous driving modes in the context of mode awareness, learning and information overload, must be standardised across all brands.
- It is important to acknowledge that brand experience includes, next to visual, auditory, and haptic experience, also a brand appropriate HMI behaviour through e.g., vehicle dynamics.

7. Conclusions

In this final chapter, an overview is provided of the general HMI Design Guidelines. This overview summarizes the knowledge developed within the MEDIATOR project which can be generally applied to HMIs of partially automated driving systems. Note that specific recommendations towards HMI design in relation to specific knowledge gaps, are listed in the final sections of the respective chapters.

From design guidelines to design guidelines

At the beginning of the MEDIATOR project, five preliminary HMI Design Guidelines have been defined to form the basis for designing an HMI that establishes a safe interaction between a semi-automated driving system and a human driver. They were designated to frame the design process, to ensure that despite the variety of to be investigated use-cases, we would still end up with one coherent HMI.

In hindsight, Design Principles would have been a better phrasing as they were indeed preliminary, while ‘Guidelines’ implies a final result. Those initial guidelines were also designated to frame the design process, to ensure that despite the variety of to be investigated use-cases, we would still end up with one coherent HMI. Hence, the term preliminary guidelines.

In this chapter however, guidelines are no longer preliminary. They are MEDIATOR’s general Design Guidelines, as they have been derived from the evaluations of the developed Mediator HMI concepts.

7.1. General HMI design guidelines

Embrace a holistic approach

The safety of a partially automated driving system is based on the driver being continuously aware of the current driving mode and the related responsibilities of the driver, as well as the system’s capabilities and limitations. Holistically, communicating driving modes should enable continuous awareness in a non-intrusive way and without needing much information-processing capacity. Holistic communication of the driving modes can, for example, be established by ambient lighting as was done in the MEDIATOR project. The fact that the driving modes were continuously communicated with ambient lighting, was highly appreciated by users of the Mediator system. Based on the findings it can also be concluded that, at least with unexperienced users, holistic, abstract communication means should be accompanied with more concrete information on what is expected and allowed from the driver’s perspective. This can provide a learning environment in which, with experience, the information provided, becomes more and more abstract and indirect, taking less processing capacity from the driver (see 3.2)

Design a generic transfer ritual

Predictability of a system is essential in establishing an interaction that is trusted, reliable, and comprehensible. Therefore, within MEDIATOR project, a standard ritual was developed based on which, HMI information flows to address the different use-cases were designed. Whereas the order and number of the different ritual-parts remain the same, timings and displays are adapted according to the situation at hand. The results showed that the Mediator ritual was generally appreciated and understood by users. This provides a strong indication that a fixed ritual is valuable, and on top of that it provides support for the specific ritual as it has been developed within Mediator (see 2.1).

Design for learned affordances

Well known activities and information cost much less mental effort to perform and process compared to new activities and information. Relate concepts and activities to existing knowledge and experience of people saves mental energy and therefore increases chances that people may perform these new activities safely. That is also the reason why people are very prone to developing habits in daily life. Within MEDIATOR project the HMI concepts were, as much as possible, based on existing affordances, such as concrete icons, the application of the gear shifter in transferring between modes, a seatbelt pull to indicate urgency, and escalating sound patterns in case of an urgent takeover request (see 2.1, 4.2 and 4.3).

Design for user acceptance

Driver autonomy is deemed crucial for user acceptance of partially autonomous vehicles. Specifically, in the case of negotiations, information on the reason for a proposed autonomous mode by the DL, is important to evoke trust and persuade the driver to follow the recommendation.

Design for industry acceptance

The validity and importance to construct legislation and guidelines such that the design space to express a brand identity is being confirmed. At the same time, it became clear that there are limitations, specifically if it comes to mode transfers and mode awareness across vehicles and across brands.

7.2. Limitations & recommendations for future research

Timing intervals in transfer rituals

In the single ritual by which the HMI guides the driver through all interactions, the timing of the intervals proved difficult to determine because, in principle, these are dynamic with the change of speed. In the HF vehicle, signal intervals of 30, 10 and 3 seconds before the end of automation and takeover gave good results, although in a fixed scenario. In the TI vehicle changes in speed, and therefore time to the end of automation (remaining time budget), was automatically and frequently recalculated, adapting the signal time-intervals. In terms of user preferences, no common result was found but we do know that driver preference changes over time, with their driving experience and experience with the system.

Further research should address studies in which a spread of driver experience directs sample composition, and in which driving time spreads over multiple drives with longer duration.

Driver-automation negotiations

With respect to the design guideline Design for User Acceptance, in early literature studies and from other domains, we have learned that driver autonomy is a key factor and intertwined with comfort and trust. On the other hand, it is in the interest of all if the driver makes choices that are safe and sustainable. Reuniting these two perspectives can be considered as "libertarian paternalism". Sunstein & Thaler (2008) advocate this approach in which the deliberate design of a choice architecture nudges consumers towards personally as well as socially desirable behaviours. Well-designed choice architectures may compensate for irrational decision-making biases, to improve consumer welfare. While only a literature study on this topic was foreseen, a negotiation ritual between driver and HMI was designed in an earlier design iteration. Further research should extent on this issue by experimentally investigate the effects of different variations of the negotiation ritual, based on theoretical principles such as the proposed ‘choice architecture’ by Sunstein & Thaler (2008).

Cognitive response versus brand experience

The design guideline Design for Industry Acceptance suggests identifying so-called design space in policies and legislation, to allow OEM brand identity variations in their HMI design. While we have been able to acknowledge the value of the guideline in the latter phases of MEDIATOR, a thorough study into how to specifically define design space boundaries, has not been possible due to Covid19 restrictions during the main partner for this study.

Further research is foreseen to set-up research by design projects at several OEMs, redesigning a baseline HMI into brand appropriate versions. In human centred studies driver understanding is measured by the speed of their cognitive response, either skill-based, rule-based, or knowledge-based, as a trade-off to brand experience.

Education system through HMI

A common finding throughout the Mediator studies is that for completely new functionalities, some form of driver education or instruction is needed. Our hypothesis is that, if a new functionality is not an upgrade, customization, or modification from an earlier function or interaction, and if it cannot sufficiently build on learned affordances a user of the system has to be instructed.

Further research is foreseen to investigate if and how driver instruction or learning may be fully fulfilled by the HMI, possibly combined with the conditional and/or stepwise release of autonomous functionalities to a specific driver. A proposed strategy would be to start from an inventory of HMIs with educational or instructional functionality in other domains, and literature research into autonomous education systems. Resulting functional requirements will then inform HMI concept design for studies and design iterations.

Long-term effects

Experience with a system may affect or even alter the behavioural effects of the system over time. Over time the interaction with a system may improve due to learning in terms of reaction times, comprehension etc. but also behavioural adaptations may follow. Behavioural adaptations are unintended behavioural changes due to an introduced system and or system-change. which were not intended by the initiators of the system (-change). A well-known example of behavioural adaptation within the driving domain is more risk full driving behaviour when having Advanced Cruise Control (Hoedemaeker & Brookhuis, 1998; Weinberger, 2001). Also, for the Mediator system more positive as well as disadvantageous effects may arise over time, although these are not specifically addressed within the project. Future research should also entail longitudinal studies since the effects of experience with a system should be considered.

Human driver characteristics

'Human driver characteristics' were designated as a secondary knowledge gap, to be investigated if the opportunity would surface in other studies. Because of COVID restrictions, these opportunities remained minimal. A consistent topic throughout the studies and across our research platforms was the desire for adaptability or personalisation of the HMI. For example, the information needs are lower for experienced drivers. Participants also regularly expressed they would want to adjust their own settings, e.g., the frequency by which an available autonomous driving is proposed. In conclusion, personalisation of the HMI by potential users is important but should be further addressed in future research.

Qualitative research

The aim of the MEDIATOR project was to develop a system for drivers in semi-automated and highly automated vehicles, resulting in safe, real-time switching between the human driver and automated system based on who is most fit to drive. In accomplishing this, a holistic HMI has been developed which should be experienced by the driver as one integrated communicating system , although it consists of different underlying concepts. The full design consists of many elements and each of these elements can be shaped in many ways. A great part of the development and evaluation of the HMI has been done by qualitative research by design, addressing in each cycle the complete design. A more traditional experimental approach would entail quantitatively assessing the effects of manipulations of just one or two elements. Such a method would entail interesting knowledge but could not address a holistic design and would not facilitate improvements within the projects' timelines (see also Tinga et al. (2023).

References

Akerstedt, T., & Gillberg, M. (1990). Subjective and objective sleepiness in the active individual. . *International Journal of Neuroscience, 52*, 29–37.

Borowsky, A., Schwarz-Chassidim, H., Hollander, C., Rauh, N., Enhuber, S., Oron-Gilad, T., & Beggiato, M. (2023a). *On-road evaluations of the vehicle-integrated Mediator system, Deliverable D3.4 of the H2020 project MEDIATOR.*

Borowsky, A., Schwarz-Chassidim, H., Hollander, C., Rauh, N., Enhuber, S., Oron-Gilad, T., & Beggiato, M. (2023b). Results of the MEDIATOR driving simulator evaluation studies, Deliverable D3.3 of the H2020 project MEDIATOR.

Carsten, O., & Martens, M., H. (2019). How can humans understand their automated cars? HMI principles, problems and solutions. *Cognition, Technology & Work*(21), 3-20. doi:10.1007/s10111-018-0484-0

Christoph, M., Cleij, D., Ahlström, C., Bakker, B., Beggiato, M., Borowsky, A., & Van Nes, C. N. (2019). *Mediating between human driver and automation: state-of-the art and knowledge gaps. D1.1 of the H2020 project MEDIATOR.*

Fiorentino, A., Ahlström, C., Anund, A., Beggiato, M., Borowsky, A., Busiello, A., . . . van Grondelle, E. D. (2023). *Recommendations legal and regulatory aspects, Deliverable D4.5 of the H2020 project MEDIATOR.*

Gaffary, Y., & Lécuyer, A. (2018). The Use of Haptic and Tactile Information in the Car to Improve Driving Safety: A Review of Current Technologies. *Frontiers in ICT, 5*. doi:10.3389/fict.2018.00005

Grondelle, E. D. v. (2016). Form Follows Panic, Discourse in Design Perspectives. . *FORM Design Magazine(263),* 82-85.

Grondelle, E. D. v., Zeumeren, I. v., F., B., Borowsky, A., Chandran, T., Cleij, D., & Christoph, M. (2021). *HMI Functional Requirements, D1.5 of the H2020 project MEDIATOR.*

Ho, C., Hong, Z. T., & Spence, C. (2005). Using spatial vibrotactile cues to direct visual attention in driving scenes. *Transportation Research Part F: Traffic Psychology and Behaviour, 8*(6), 397-412. doi:10.1016/j.trf.2005.05.002

Hoedemaeker, M., & Brookhuis, K. A. (1998). Behavioral adaptation to driving with an adaptive cruise control (ACC). . *Transp Res Part F, 1*(2), 95–106.

Lu, Z., Happee, R., Cabrall, C. D. D., Kyriakidis, M., & de Winter, J. C. F. (2016). Human factors of transitions in automated driving: A general framework and literature survey. *Transportation Research Part F: Traffic Psychology and Behaviour, 43*, 183-198. doi:10.1016/j.trf.2016.10.007

Muthumani, A., & Wang, D. (2022, 19-20 October 2022). *Human-machine interface designs assisting drivers of automated vehicles during transitions: evaluation from an end-user perspective.* Paper presented at the THE 8TH INTERNATIONAL CONFERENCE ON DRIVER DISTRACTION AND INATTENTION, Gothenburg.

Naujoks, F., Purucker, C., & Neukum, A. (2016). Secondary task engagement and vehicle automation – Comparing the effects of different automation levels in an on-road experiment. *Transportation Research Part F: Traffic Psychology and Behaviour, 38*, 67-82. doi:10.1016/j.trf.2016.01.011

NHTSA. (2011). *Using Haptic Feedback to Increase Seat Belt Use*. Retrieved from Washington DC, USA: https://www.google.com/url?sa=i&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=0CAIQw7AJahcKEwiAyr_pq5iAAxUAAAAAHQAAAAAQAg&url=https%3A%2F%2Frosap.ntl.bts.gov%2Fview%2Fdot%2F2054%2Fdot_2054_DS1.pdf%3F&psig=AOvVaw047GmBYyddx6Iqr3FgZLqM&ust=1689772602730817&opi=89978449

NHTSA. (2016). *Visual-Manual NHTSA Driver Distraction Guidelines for In-Vehicle Electronic Devices.* Retrieved from Washington DC, USA: https://www.federalregister.gov/documents/2013/04/26/2013-09883/visual-manual-nhtsa-driver-distraction-guidelines-for-in-vehicle-electronic-devices#:~:text=The%20NHTSA%20Guidelines%20recommend%20that%20devices%20be%20designed%20so%20that,of%2012%20seconds%20or%20less

Normann, D. A. (1988). *The psychology of everyday things.* : Basic books.

Shan, Y. (2021). *Human-Machine Interaction Design for Negotiation in Highly Automated Vehicles.* Technical University Delft, Delft.

Stappers, P. J., & Giaccardi, E. (2017). Research through Design. In *The Encyclopedia of Human-Computer interaction.* (2nd ed.).

Sunstein, C. R., & Thaler, R. H. (2008). *Nudge: Improving Decisions about Health, Wealth, and Happiness*: Yale University Press.

Tinga, A. M., Cleij, D., Jansen, R. J., van der Kint, S., & van Nes, N. (2022). Human machine interface design for continuous support of mode awareness during automated driving: An online simulation. *Transportation Research Part F: Traffic Psychology and Behaviour, 87*, 102-119. doi:10.1016/j.trf.2022.03.020

Tinga, A. M., van Zeumeren, I. M., Christoph, M., van Grondelle, E., Cleij, D., Aldea, A., & van Nes, N. (2023). Development and evaluation of a human machine interface to support mode awareness in different automated driving modes. *Transportation Research Part F: Traffic Psychology and Behaviour, 92*, 238-254. doi:10.1016/j.trf.2022.10.023

Weinberger, M. (2001). *Der Einfluss von Adaptive Cruise Control Systemen auf das Fahrverhalten (The influence of Adaptive Cruise Control on driving behavior).* . TU München, Aachen.

Appendix A: Take over experience during piloted driving