Best practices for design and development of HMI systems

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Author(s)	Rebeca I. García Betances (TREE)
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Author(s)

Name	Organisation	Name	Organisation
Rebeca I. García Betances	TREE		

Reviewers

Name	Organisation	Date
Thomas Weisswange	HRI-EU	2025-05-19
Robert Leute	MAR	2025-05-22

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Version	Date	Name/Organisation	Description
V0.1	2025-01-13	TREE	Initial version – ToC, structure and summary of previous work.
V1.0	2025-04-01	TREE	Inputs from HEIDI partners added (questionnaire)
V1.5	2025-04-30	TREE	Inputs from HEIDI partners added (workshop)
V2.0	2025-05-14	TREE	Version for revision by Internal Reviewers.
V2.1	2025-05-26	TREE	Reviewers' comments addressed.
V3.0	2025-05-26	TREE; VIF	Final version for internal quality check and submission.

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1. Executive Summary

The present deliverable consolidates the lessons learnt and insights gained from the activities conducted under WP5 activities, as well as from the work produced within the design and development activities (WP1; WP2; WP3; WP4) and the studies and validations performed (WP7). The information collected was structured into eight guidelines and implemented by the formulation of best practices targeted to different profiles such as: technology developers and manufacturers, technology providers, policymakers, standardization organizations, etc.

The final aim of this report is to produce operational guidelines for design and development of HMI systems, on road-going vehicles for cooperative interaction with pedestrians and other road users, also contributing to best conceptualization, design, development and validation practices. Project partners have been engaged across various phases of the project lifecycle, collaborating across work packages and participating in surveys and workshops.

The structure of the main sections of the deliverable is the following:

Section 3 outlines the key practical guidelines to provide recommendations to future technology developers and manufacturers, technology providers, policymakers or other key stakeholders during the lifecycle of the design and development of HMI systems. These guidelines derived from the deliverables produced during the design, testing, and validation phases of the HEIDI project.

Section 4 aims to provide insights to implement the defined key guidelines by presenting different best practices on how to implement each guideline. The operational best practices were also discussed with HEIDI partners through their inputs to a questionnaire (Annex I) and their participation in a brainstorming session as part of WP5 activities. Finally, we highlighted each best practice, the guideline(s) which it pertains to, the relevant target stakeholder, the phase of development when this practice should be implemented, and their impact in the development and implementation lifecycle of HMI on road-going vehicles.

Keywords: guidelines, lessons learnt, best practices, stakeholders, recommendations, design and development, HMI systems.

2. Objectives

The primary objective of deliverable 5.5 is to produce operational guidelines for design and development of HMI systems, also contributing to best conceptualization, design, development and validation practices, including to ensure user's security and privacy aspects. As part of WP5, this objective complements HEIDI's main objective 4 related to the elaboration of recommendations for regulation, standardisation, and development of adaptive internal and external HMIs.

To reach this objective, first we have revised HEIDI's deliverables from tasks to collect the main conclusions, lessons learnt, recommendations derived from the activities conducted during the design (WP1), development (WP2, WP3, WP4), testing (WP5), and validation (WP7) phases of the HEIDI project. With this information a questionnaire was elaborated and circulated to all project partners (Annex I), to identify the most significant lessons learnt, the challenges encountered, and the insights and recommendations that have emerged during project activities and to outline and define key guidelines. Additionally, a workshop was organized to discuss the defined guidelines with HEIDI partners and gather ideas and opinions about the way to implement each guideline.

2.1 Background

The report seeks to consolidate the findings from the completed tasks and prior deliverables produced throughout HEIDI work packages, utilising the lessons learnt, conclusions and recommendations of the deliverables and outcomes to formulate practical guidelines on the best conceptualization, design, development and validation practices, including to ensure user's security and privacy aspects. The following are the deliverables and information taken into consideration:

- ✓ D5.2 – State of the Art on validation methods for cooperative and adaptive HMI solutions:
  - Main findings and considerations for the HEIDI project: adaptive iHMIs, eHMIs, and co-simulation.
- ✓ D5.3 – Results and conclusion from the validation tests:
  - General conclusions.
  - Study limitations and lessons learnt.
- ✓ D5.4 – Initial recommendations for Legal Framework and Standardization:
  - Recommendations of eHMI regulations: placement, optical requirements, messages, patterns to be displayed.
  - Recommendations for Vehicle/System requirements: limitations on use of eHMI.
- ✓ First results and conclusions from WP7 evaluation tests.

2.2 Key target audience and technologies

The key target audience addressed by the defined guidelines and best practices are the following:

- Technology developers and Manufacturers
- Technology providers
- Scientific community

- Policymakers
- Standardization bodies
- Legislation, security and/or privacy experts
- Public Authorities
- General Public

The guidelines and best practices reported apply to technologies related to the design, development and implementation of internal and/or external HMIs systems on road-going vehicles for cooperative interaction with pedestrians and other road users. They also apply to the technologies used throughout the development of HEIDI outcomes such as the osmotic layer, fluid iHMI, fluid eHMI, cooperative HMI, sensing & behavioural predictive models, and co-simulations; that have been mapped and described in deliverables from WP2, WP3 and WP4.

3. Practical guidelines for stakeholders

In the following section we have identified and described a set of guidelines coming from lessons learnt from HEIDI activities. These guidelines are identified to be useful to one or several phases of the development of HMI systems life cycle. These phases are: (i) Desing and Development: concept mapping, methodology design, technological design and development; (ii) community engagement, (iii) validation and piloting; (iv) deployment, maintenance and exploitation; and (v) research and policymaking. Figure 3–1 presents the guidelines, and the principal concept associated with the best practices derived from them.

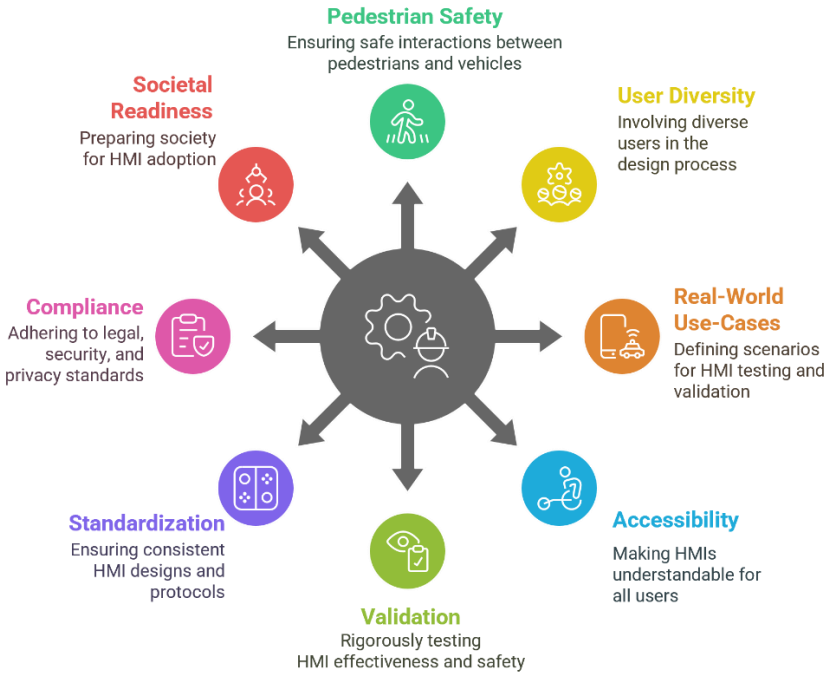


Figure 3–1: Guidelines for the development and implementation of HMI systems.

3.1 Guideline 1: Address impacts of cooperative HMI systems for pedestrian-vehicle interactions

To ensure safe, effective, and socially acceptable pedestrian-vehicle interactions, cooperative Human-Machine Interface (HMI) systems must be designed through an iterative, user-centred approach that emphasizes clear and perceivable communication, real-world validation, and ongoing monitoring of impacts. Building on the HEIDI project's experiences, the development and deployment of such systems should integrate practical traffic studies, continuous stakeholder feedback, and proactive mitigation of unintended consequences to ensure both pedestrian understanding and trust, as well as system reliability in diverse urban environments and traffic conditions.

Table 3-1: Best practices to implement guideline 1

Best practice nº	Best practice to implement guideline	Target stakeholders	Development phase
1.1	Consider Mounting / Placement of an eHMI on a roadgoing vehicle: visual communication to be perceivable and unambiguous for all pedestrian and road vehicles.	Tech developers and Manufacturers & Tech providers	Concept mapping & design; deployment
1.2	Systematic Requirements & Monitoring highlight the importance of iterative design: testing, evaluating real-world feedback, and addressing potential unintended consequences.	Tech developers and Manufacturers & Tech providers	All phases
1.3	Continuously monitor the technology for unexpected negative impacts and iterate early.	Tech developers and Manufacturers & Tech providers	Concept mapping & Design; Validation & piloting
1.4	Investigate and mitigate any unintended consequences of HMI interactions.	Tech developers and Manufacturers & Scientific community	Concept mapping & Design; Validation & piloting
1.5	Engage with pedestrians and drivers to gather feedback and iteratively improve the system.	Tech developers and Manufacturers & Scientific community	Concept mapping, Design; Validation & piloting
1.6	Conduct practical studies in real traffic conditions.	Tech developers and Manufacturers & Scientific community	Validation & piloting
1.7	Determine, address and monitor the effects of the design and methods designed for the validation phase on the study participants.	Tech developers and Manufacturers & Scientific community	Validation & piloting

3.2 Guideline 2: Involve end users and be sensitive to diversity

In order to create inclusive and ethically responsible cooperative HMI systems, it is essential to actively involve end users—especially those from diverse backgrounds—throughout the entire design and development process. Drawing from the HEIDI project experiences, this involves co-design practices that bring together developers, legal and ethics experts, and a broad spectrum of users to formulate requirements, conduct real-world testing, and ensure that the system addresses the varied needs, abilities, and expectations of all road users. This inclusive approach supports usability, fairness, and social acceptance as the technology matures.

Table 3-2: Best practices to implement guideline 2

Best practice nº	Best practice to implement guideline	Target stakeholders	Development phase
2.1	Balance the needs of different groups and individuals.	Tech developers and Manufacturers & Tech providers	Concept mapping & design Community engagement, validation & piloting
2.2	Formulate requirements in collaboration with developers, ethics and legal experts, and those testing the tools.	Tech developers and Manufacturers	Concept mapping & Design
2.3	Use a co-design approach towards defining HMIs on a roadgoing vehicle.	Tech developers and Manufacturers & Tech providers	Concept mapping, design & development Community engagement, validation & piloting
2.4	Use a co-design approach that includes diverse user groups from the earliest stages of development.	Tech developers and Manufacturers & Scientific community	All phases
2.5	Conduct regular usability testing with a focus on inclusion, ensuring that the HMI is accessible to users with different needs and backgrounds.	Tech developers and Manufacturers, Tech providers & Scientific community	Community engagement, Validation & piloting
2.6	Conduct a broad study with diverse types of road users in a relevant environment according to the current and expected TRL – Technology Readiness Level.	Tech developers and Manufacturers & Tech providers	Validation & piloting

3.3 Guideline 3: Define relevant use-cases

It is essential to define comprehensive use-cases grounded in real-world pedestrian-vehicle interactions and user needs. As lessons learnt in the HEIDI project validations, this involves identifying diverse, representative scenarios that include various road users and vehicle types, including both common and edge-case situations. These use-cases should guide design, testing, and validation efforts, using both simulations and field tests to ensure that HMIs function reliably across regulated and unregulated interactions in dynamic traffic environments.

Table 3-3: Best practices to implement guideline 3

Best practice nº	Best practice to implement guideline	Target stakeholders	Development phase
3.1	Identify relevant user needs, use-cases and situations where HMIs shall be deployed.	Tech developers and Manufacturers & Scientific community	Concept mapping, design & development
3.2	The definition of the use cases should be based on the user needs.	Tech developers and Manufacturers & Scientific community	Concept mapping, design & development
3.3	The use-cases should involve different road users and vehicles.	Tech developers and Manufacturers & Scientific community	Concept mapping, design & development
3.4	Develop detailed use-case scenarios based on real-world interactions between vehicles and pedestrians.	Tech developers and Manufacturers & Scientific community	Concept mapping, design & development
3.5	Identify a generalized use-case for testing different unregulated interactions or situations that are not represented in the other use-cases.	Tech developers and Manufacturers & Scientific community	Concept mapping, design & development
3.6	For the validations and evaluations select the more representative use cases.	Tech developers and Manufacturers & Scientific community	Validation & piloting
3.7	Validate these use-cases through simulations and field tests to ensure they cover a wide range of potential situations.	Tech developers and Manufacturers & Scientific community	Validation & piloting

3.4 Guideline 4: Be understandable and accessible

HMIs design must prioritize clarity, accessibility, and user comprehension across diverse populations. This involves creating intuitive, explainable messages using validated symbols and optical parameters that are clearly visible without causing discomfort. Researchers should collaborate with UI experts and end users—including individuals with disabilities and from various cultural backgrounds—to iteratively test and refine HMI elements. Supporting materials must accompany the system to clearly communicate functionality and message meaning, ensuring broad understanding and acceptance in real-world contexts.

Table 3-4: Best practices to implement guideline 4

Best practice nº	Best practice to implement guideline	Target stakeholders	Development phase
4.1	Design understandable and accessible messages which shall be conveyed by eHMIs.	Tech developers and Manufacturers & Tech providers	Concept design & development
4.2	Ensure that optical parameters are well addressed for appropriate visibility while avoiding glare and discomfort.	Tech developers and Manufacturers & Tech providers	Concept design & development
4.3	Identify and validate with end-users the requirements on symbols and patterns to be used for messages.	Tech developers and Manufacturers & Tech providers	Concept design & development Community engagement, validation & piloting.
4.4	Develop transparent and explainable tools.	Tech developers and Manufacturers & Tech providers	Concept design & development Validation & piloting
4.5	Incorporate UI experts to design HMI interfaces with clear, intuitive symbols and messages that are easily understood, including different ethnicities and users with disabilities.	Tech developers and Manufacturers & Tech providers	Concept design & development
4.6	Collect feedback from study and validation participants regarding the understanding and accessibility of the HMIs.	Tech developers and Manufacturers, Tech providers; Scientific Community	Community engagement; Validation & piloting.
4.7	Provide proper information material for end-users with clear explanation on how to use the system and the meaning of messages and signals.	Tech developers and Manufacturers & Tech providers	All phases

3.5 Guideline 5: Comprehensive methodologies, validations and evaluation tests

To rigorously assess the effectiveness, safety, and user acceptance of cooperative HMI systems, it is essential to apply comprehensive, multi-method evaluation methodologies. Based on the conclusions of HEIDI's validation methods and studies performed, methodologies should include cross-over designs to address individual differences and realistic scenarios that balance experimental control with ecological validity. Thoughtful participant selection and ongoing feedback collection further ensure meaningful insights.

Table 3-5: Best practices to implement guideline 5

Best practice nº	Best practice to implement guideline	Target stakeholders	Development phase
5.1	Conduct larger-scale studies to enhance statistical robustness, reliability, and generalizability.	Tech developers and Manufacturers & Scientific community	Methodology design; Validation & piloting
5.2	Use a combination of subjective and objective validation methods.	Tech developers and Manufacturers & Scientific community	Methodology design; Validation & piloting
5.3	Prefer cross-over designs over between-subject designs to account for individual differences.	Tech developers and Manufacturers & Scientific community	Methodology design; Validation & piloting
5.4	Conduct thorough pilot testing with the full protocol, ensuring logged data checks.	Tech developers and Manufacturers & Scientific community	Validation & piloting
5.5	Avoid using completely naïve participants to ensure meaningful responses to HMI features.	Tech developers and Manufacturers & Tech providers; Scientific community	Validation & piloting
5.6	Minimize participant burden by selecting only the most relevant questionnaire items.	Tech developers and Manufacturers & Scientific community	Methodology design; Validation & piloting
5.7	Integrate timely feedback collection during user interaction to capture immediate impressions and reactions.	Tech developers and Manufacturers & Scientific community	Methodology design; Validation & piloting
5.8	Consider participant-specific sensitivities or limitations during recruitment to ensure safety and data quality.	Tech developers and Manufacturers & Scientific community	Methodology design; Validation & piloting
5.9	Design driving scenarios and test environments to minimize discomfort and use a combination of subjective reports and objective data to evaluate user experience.	Tech developers and Manufacturers & Scientific community	Methodology design; Validation & piloting
5.10	Combine questionnaires and interviews for a more detailed understanding of participant experiences.	Tech developers and Manufacturers & Scientific community	Methodology design; Validation & piloting
5.11	Use a mix of simulations, field tests, and user feedback to validate the HMI's effectiveness and reliability.	Tech developers and Manufacturers & Scientific community	Methodology design; Validation & piloting

3.6 Guideline 6: Standardize HMI designs and communication protocols

To promote safety, interoperability, and user trust in cooperative HMI systems, the standardization of HMI designs and communication protocols is essential. As emphasized by the HEIDI project, consistent use of symbols, colours, message structures, and behavioural cues across vehicle types and contexts enables pedestrians and drivers to interpret HMI signals reliably and intuitively. Establishing harmonized design frameworks and shared communication standards—validated through user testing and cross-industry collaboration—lays the foundation for scalable, inclusive, and regulation-ready deployment of HMI technologies across Europe and beyond.

Table 3-6: Best practices to implement guideline 6

Best practice nº	Best practice to implement guideline	Target stakeholders	Development phase
6.1	Standardizing HMI designs and communication protocols (between road users and vehicle), ensuring consistency across different vehicle manufacturers.	Policy makers and Standardization Organizations	Deployment & policymaking
6.2	Standardized HMI evaluation protocols (and KPIs).	Policy makers and Standardization Organizations	Deployment & policymaking
6.3	Universally understood eHMIs for pedestrian-vehicle interactions.	Policy makers and Standardization Organizations	Deployment & policymaking
6.4	Ensure that methodologies are standardized within technological development policies.	Policy makers and Standardization Organizations	Concept mapping, design & policymaking
6.5	Establish communication channels with a diverse range of external stakeholders, outside of the R&D process.	Tech developers and Manufacturers, Tech providers; Scientific Community; Policy makers and Standardization Organizations	All phases
6.6	Work with industry standards organizations to develop universal guidelines for HMI designs and communication protocols.	Tech developers and Manufacturers, Tech providers; Scientific Community; Policy makers and Standardization Organizations	Deployment & policymaking
6.7	Ensure that these standards are adopted across different vehicle manufacturers to maintain consistency.	Tech developers and Manufacturers, Tech providers; Scientific Community; Policy makers and	Deployment & policymaking

		Standardization Organizations	
6.8	Joint effort with standardization entities (Euro-NCAP, etc.).	Tech developers and Manufacturers, Tech providers; Scientific Community	All phases

3.7 Guideline 7: Ensure legal, security and privacy compliance

Ensuring responsible development and deployment of cooperative HMI systems, legal, security, and privacy compliance must be embedded from the outset. In line with the HEIDI project's approach, this includes adhering to data protection regulations (e.g. GDPR), securing communication channels to prevent misuse or manipulation, and clearly defining legal responsibilities in human-machine interactions. Proactive collaboration with legal, ethical, and cybersecurity experts throughout the design and validation process is crucial to safeguard user rights, build public trust, and ensure that HMI technologies operate within a transparent and accountable regulatory framework.

Table 3-7: Best practices to implement guideline 7

Best practice nº	Best practice to implement guideline	Target stakeholders	Development phase
7.1	Include experts in AI legal frameworks, security principles throughout the HMIs technical development and solution deployment.	Tech developers and Manufacturers, Tech providers; Legislation, security and/or privacy experts.	Concept design, development & deployment.
7.2	Map and identify the applicable AI ethical principles and legal frameworks for each phase of the R&D process to which they are relevant.	Tech developers and Manufacturers, Tech providers; Legislation, security and/or privacy experts.	Concept design, development & deployment.
7.3	Utilize ethics-by-design methodologies, including comprehensive and iterative ethical impact assessments	Tech developers and Manufacturers, Tech providers; Legislation, security and/or privacy experts.	Concept design, development & deployment.
7.4	Utilize security-by-design and security-by-default methodologies by identifying and implementing appropriate measures to manage risks to network security and information systems.	Tech developers and Manufacturers, Tech providers; Legislation, security and/or privacy experts.	All phases
7.5	Consult with legal experts to ensure compliance with all relevant regulations and standards, conduct	Tech developers and Manufacturers, Tech providers;	All phases

	regular audits to maintain compliance.	Legislation, security and/or privacy experts.	
7.6	Make suggestions that require changes to legislation based on validation phases and conclusions.	Tech developers and Manufacturers, Tech providers; Legislation, security and/or privacy experts; Policymakers	Validation & policymaking

3.8 Guideline 8: Promote Societal Readiness and Public Acceptance

To ensure successful adoption of cooperative HMI systems, societal readiness must be prioritized through inclusive engagement, transparent communication, and alignment with societal values and expectations. Following the HEIDI project and recent EU guidance, this involves involving citizens early in the innovation process, addressing ethical and social concerns, and building trust through responsiveness, inclusivity, and demonstrable public benefit.

Table 3-8: Best practices to implement guideline 8

Best practice nº	Best practice to implement guideline	Target stakeholders	Development phase
8.1	Engage citizens early and continuously in the development process to ensure the technology aligns with real societal needs and values.	Tech developers and Manufacturers, Tech providers; Scientific Community	All phases
8.2	Ensure transparent communication about HMI system capabilities, limitations, benefits, and risks, to build public trust and informed consent.	Tech providers & Public Authorities.	Deployment & exploitation
8.3	Systematically assess the ethical, legal, and social implications of HMI deployment to anticipate societal concerns and avoid unintended consequences.	Tech developers and Manufacturers, Tech providers; Legislation, security and/or privacy experts; Policymakers	Validation & piloting; Policymakers
8.4	Prepare demonstrations in real traffic environments to showcase benefits, gather feedback for the public, and promote societal acceptance through visibility and dialogue.	Tech developers and Manufacturers, Tech providers; Scientific Community; General Public.	Piloting, deployment & exploitation

4. Summary of best practices to implement guidelines

The following table presents a summary of the identified best practices depicted for each relevant stakeholders and corresponding R&D lifecycle phases. Each of the best practices are numbered so that stakeholders can easily access those practices which are relevant for them.

Table 4-1: Summary of best practices for stakeholders.

Relevant Stakeholder	Lifecycle phase			
	Design and Development: Concept mapping, methodology, design & development	Community engagement. Validation & pilots	Deployment, maintenance & exploitation	Research & policymaking
Tech developers and Manufacturers	1.1 – 1.5, 2.1 – 2.4, 3.1 – 3.5, 4.1 – 4.5, 4.7, 5.1 – 5.3, 5.6 – 5.11, 6.5, 6.8, 7.1 – 7.5, 8.1	1.2 – 1.7, 2.3 – 2.6, 3.6, 3.7, 4.4, 4.6, 4.7, 5.1 – 5.11, 6.5, 6.8, 7.4 -7.6, 8.1, 8.3, 8.4	1.1, 1.2, 2.4, 4.7, 6.5, 6.6, 6.7, 6.8, 7.1, 7.2, 7.3, 7.4, 7.5, 8.1, 8.4	1.2, 2.4, 4.7, 6.5, 6.6, 6.7, 6.8, 7.4, 7.5, 7.6, 8.1, 8.3
Tech providers	1.1, 1.2, 1.3, 2.1, 2.3, 4.1 – 4.7, 6.5, 6.8, 7.1 – 7.5, 8.1	1.2, 1.3, 2.3, 2.5, 2.6, 4.4, 4.6, 4.7, 5.5, 6.5, 6.8, 7.4, 7.5, 7.6, 8.1, 8.3, 8.4	1.1, 1.2, 4.7, 6.5, 6.6, 6.7, 6.8, 7.1, 7.2, 7.3, 7.4, 7.5, 8.1, 8.2, 8.4	1.2, 4.7, 6.5, 6.6, 6.7, 6.8, 7.4, 7.5, 7.6, 8.1, 8.3
Scientific community	1.4, 1.5, 2.4, 3.1, 3.2, 3.3, 3.4, 3.5, 5.1, 5.2, 5.3, 5.6, 5.7, 5.8, 5.9, 5.10, 5.11, 6.5, 6.8, 8.1	1.4 – 1.7, 2.4, 2.5, 3.6, 3.7, 4.6, 5.1 – 5.11, 6.5, 6.8, 8.1, 8.4	2.4, 6.5, 6.6, 6.7, 6.8, 8.1, 8.4	2.4, 6.5, 6.6, 6.7, 6.8, 8.1
Policymakers	6.4, 6.5	6.5, 8.3	6.1, 6.2, 6.3, 6.5, 6.6, 6.7	6.1, 6.2, 6.3, 6.4, 6.5, 6.6, 6.7, 8.3
Standardization bodies	6.4, 6.5	6.5	6.1, 6.2, 6.3, 6.5, 6.6, 6.7	6.1, 6.2, 6.3, 6.4, 6.5, 6.6, 6.7
Legislation, security and/or privacy experts	7.1, 7.2, 7.3, 7.4, 7.5	7.4, 7.5, 8.3	7.1, 7.2, 7.3, 7.4, 7.5	7.4, 7.5, 8.3
Public Authorities	N/A	N/A	8.2	N/A
General Public	N/A	8.4	8.4	N/A

In Table 4-2 we summarize all the best practices to implement the guidelines, highlighting each best practice, the guideline(s) which it relates to, the relevant target audience, the phase of development when this practice should be implemented, and the expected impact of each best practice.

Best practice nº	Relevant guideline	Best practice to implement guideline	Target stakeholders	Development phase	Impact
1.1	G1	Mounting / Placement of an eHMI on a roadgoing vehicle: visual communication must be perceivable and unambiguous for all pedestrian and road vehicles.	Tech developers and Manufacturers, Tech providers	Concept mapping & design; Deployment	Ensures eHMI signals are clear, reducing misinterpretation and improving safety for all road users.
1.2	G1	Systematic Requirements & Monitoring highlight the importance of iterative design: testing, evaluating real-world feedback, and addressing potential unintended consequences.	Tech developers and Manufacturers, Tech providers	All phases	Improves system robustness and usability through iterative refinements based on real-world feedback.
1.3	G1	Continuously monitor the technology for unexpected negative impacts and iterate early.	Tech developers and Manufacturers, Tech providers	Concept mapping, Design; Validation & piloting	Minimizes risk of harm by catching negative effects early, improving user trust and system safety.
1.4	G1	Investigate and mitigate any unintended consequences of HMI interactions.	Tech developers and Manufacturers, Scientific community	Concept mapping, Design; Validation & piloting	Reduces unintended interaction issues, ensuring safer and smoother human-vehicle communication.
1.5	G1	Engage with pedestrians and drivers to gather feedback and iteratively improve the system.	Tech developers and Manufacturers, Scientific community	Concept mapping, Design; Validation & piloting	Enhances user satisfaction and system relevance by integrating actual user experiences.
1.6	G1	Conduct practical studies in real traffic conditions.	Tech developers and Manufacturers, Scientific community	Validation & piloting	Increases reliability of system performance in realistic conditions, ensuring readiness for deployment.
1.7	G1	Determine, address and monitor the effects of the design and methods designed for the validation phase on the study participants.	Tech developers and Manufacturers, Scientific community	Validation & piloting	Improves validity of studies and protects participants, ensuring ethical and accurate validation.

2.1	G2	Balances the needs of different groups and individuals.	Tech developers and Manufacturers, Tech providers	Concept mapping & design	Promotes fairness and accessibility, preventing exclusion of vulnerable or minority groups.
2.2	G2	Formulate requirements in collaboration with developers, ethics and legal experts, and those testing the tools.	Tech developers and Manufacturers	Concept mapping & Design	Enhances legal compliance and ethical soundness, reducing risk of future legal challenges.
2.3	G2	Use a co-design approach towards defining HMIs on a roadgoing vehicle.	Tech developers and Manufacturers, Tech providers	Concept mapping, design & development Community engagement, validation & piloting	Creates HMIs that better meet end-user needs, improving usability and acceptance.
2.4	G2	Use a co-design approach that includes diverse user groups from the earliest stages of development.	Tech developers and Manufacturers, Scientific community	All phases	Increases system inclusivity and user acceptance across diverse populations.
2.5	G2	Conduct regular usability testing with a focus on inclusion, ensuring that the HMI is accessible to users with different needs and backgrounds.	Tech developers and Manufacturers, Tech providers & Scientific community	Community engagement, Validation & piloting	Ensures system accessibility and usability for a wider user base, improving equity.
2.6	G2	Conduct a broad study with diverse types of road users in a relevant environment according to the current and expected TRL – Technology Readiness Level.	Tech developers and Manufacturers, Tech providers	Validation & piloting	Enhances system robustness and generalizability, increasing confidence in deployment outcomes.
3.1	G3	Identify relevant user needs, use-cases and situations where HMIs shall be deployed.	Tech developers and Manufacturers, Scientific community	Concept mapping, design & development	Aligns system functionality with real-world needs, improving practical relevance.
3.2	G3	The definition of the use cases should be based on the user needs.	Tech developers and Manufacturers,	Concept mapping, design & development	Ensures user-centred design, increasing satisfaction and usability.

			Scientific community		
3.3	G3	The use-cases should involve different road users and vehicles.	Tech developers and Manufacturers, Scientific community	Concept mapping, design & development	Increases system effectiveness across varied road users and scenarios.
3.4	G3	Develop detailed use-case scenarios based on real-world interactions between vehicles and pedestrians.	Tech developers and Manufacturers, Scientific community	Concept mapping, design & development	Provides realistic test conditions, improving predictive validity of HMI behaviour.
3.5	G3	Identify a generalized use-case for testing different unregulated interactions or situations that are not represented in the other use-cases.	Tech developers and Manufacturers, Scientific community	Concept mapping, design & development	Prepares system for edge cases and unregulated interactions, reducing future risks.
3.6	G3	For the validations and evaluations select the more representative use cases.	Tech developers and Manufacturers, Scientific community	Validation & piloting	Focuses validation on critical interactions, increasing testing efficiency and relevance.
3.7	G3	Validate these use-cases through simulations and field tests to ensure they cover a wide range of potential situations.	Tech developers and Manufacturers, Scientific community	Validation & piloting	Ensures system reliability in diverse scenarios, strengthening readiness for deployment.
4.1	G4	Design understandable and accessible messages which shall be conveyed by eHMIs.	Tech developers and Manufacturers, Tech providers	Concept design & development	Improves communication clarity, reducing misunderstanding and accidents.
4.2	G4	Ensure that optical parameters are well addressed for appropriate visibility while avoiding glare and discomfort.	Tech developers and Manufacturers, Tech providers	Concept design & development	Enhances visibility and comfort, increasing safety and user satisfaction.

4.3	G4	Identify and validate with end-users the requirements on symbols and patterns to be used for messages.	Tech developers and Manufacturers, Tech providers	Concept design & development	Ensures symbols/messages are intuitive and widely understandable, reducing confusion.
4.4	G4	Develop transparent and explainable tools.	Tech developers and Manufacturers, Tech providers	Concept design & development Validation & piloting	Increases user trust and system accountability through transparency.
4.5	G4	Incorporate UI experts to design HMI interfaces with clear, intuitive symbols and messages that are easily understood, including different ethnicities and users with disabilities.	Tech developers and Manufacturers, Tech providers	Concept design & development	Improves accessibility and inclusivity, meeting diverse user needs effectively.
4.6	G4	Collect feedback from study and validation participants regarding the understanding and accessibility of the HMIs.	Tech developers and Manufacturers, Tech providers; Scientific Community	Community engagement; Validation & piloting.	Identifies and resolves misunderstandings, improving HMI usability and acceptance.
4.7	G4	Provide proper information material for end-users with clear explanation on how to use the system and the meaning of messages and signals.	Tech developers and Manufacturers, Tech providers	All phases	Improves user onboarding and confidence, facilitating adoption and correct usage.
5.1	G5	Conduct larger-scale studies to enhance statistical robustness, reliability, and generalizability.	Tech developers and Manufacturers, Scientific community	Methodology design; Validation & piloting	Increases confidence in study outcomes, ensuring reliable evidence for decision-making.
5.2	G5	Use a combination of subjective and objective validation methods.	Tech developers and Manufacturers, Scientific community	Methodology design; Validation & piloting	Provides comprehensive validation data, improving system credibility.
5.3	G5	Prefer cross-over designs over between-subject designs to account for individual differences.	Tech developers and Manufacturers, Scientific community	Methodology design; Validation & piloting	Reduces variability from individual differences, improving result accuracy.

5.4	G5	Conduct thorough pilot testing with the full protocol, ensuring logged data checks.	Tech developers and Manufacturers, Scientific community	Validation & piloting	Ensures protocol reliability, minimizing data quality issues in large studies.
5.5	G5	Avoid using completely naïve participants to ensure meaningful responses to HMI features.	Tech developers and Manufacturers, Tech providers; Scientific community	Validation & piloting	Improves test relevance by using participants capable of meaningful interaction.
5.6	G5	Minimize participant burden by selecting only the most relevant questionnaire items.	Tech developers and Manufacturers, Scientific community	Methodology design; Validation & piloting	Reduces participant fatigue, improving data quality and study compliance.
5.7	G5	Integrate timely feedback collection during user interaction to capture immediate impressions and reactions.	Tech developers and Manufacturers, Scientific community	Methodology design; Validation & piloting	Captures authentic user experiences in real time, improving design refinement.
5.8	G5	Consider participant-specific sensitivities or limitations during recruitment to ensure safety and data quality.	Tech developers and Manufacturers, Scientific community	Methodology design; Validation & piloting	Protects participants, improving ethical standards and data validity.
5.9	G5	Design driving scenarios and test environments to minimize discomfort and use a combination of subjective reports and objective data to evaluate user experience.	Tech developers and Manufacturers, Scientific community	Methodology design; Validation & piloting	Increases participant comfort and safety, improving study reliability.
5.10	G5	Combine questionnaires and interviews for a more detailed understanding of participant experiences.	Tech developers and Manufacturers, Scientific community	Methodology design; Validation & piloting	Provides richer insight into user experiences, enhancing design improvements.

5.11	G5	Use a mix of simulations, field tests, and user feedback to validate the HMI's effectiveness and reliability.	Tech developers and Manufacturers, Scientific community	Methodology design; Validation & piloting	Ensures well-rounded validation, strengthening system effectiveness and reliability.
6.1	G6	Standardizing HMI designs and communication protocols (between road users and vehicle), ensuring consistency across different vehicle manufacturers.	Policy makers and Standardization Organizations	Deployment & policymaking	Ensures interoperability and consistent user experience across vehicles, improving safety.
6.2	G6	Standardized HMI evaluation protocols (and KPIs).	Policy makers and Standardization Organizations	Deployment & policymaking	Facilitates fair and consistent evaluation across industry, supporting regulatory compliance.
6.3	G6	Universally understood eHMIs for pedestrian-vehicle interactions.	Policy makers and Standardization Organizations	Deployment & policymaking	Improves pedestrian understanding and safety globally.
6.4	G6	Ensure that methodologies are standardized within technological development policies.	Policy makers and Standardization Organizations	Concept mapping, design & policymaking	Embeds safety and inclusivity into design from the start, improving policy alignment.
6.5	G6	Establish communication channels with a diverse range of external stakeholders, outside of the R&D process.	Tech developers and Manufacturers, Tech providers; Scientific Community; Policy makers and Standardization Organizations	All phases	Enhances stakeholder buy-in and improves design relevance by broadening perspectives.
6.6	G6	Work with industry standards organizations to develop universal guidelines for HMI designs and communication protocols.	Tech developers and Manufacturers, Tech providers; Scientific Community; Policy makers and Standardization Organizations	Deployment & policymaking	Supports consistent application of best practices, improving cross-industry adoption.

6.7	G6	Ensure that these standards are adopted across different vehicle manufacturers to maintain consistency.	Tech developers and Manufacturers, Tech providers; Scientific Community; Policy makers and Standardization Organizations	Deployment & policymaking	Ensures wide-scale consistency, improving usability and safety across vehicle brands.
6.8	G6	Joint effort with standardization entities (Euro-NCAP, etc.).	Tech developers and Manufacturers, Tech providers; Scientific Community	All phases	Increases credibility and acceptance of standards, accelerating deployment and compliance.
7.1	G7	Include experts in AI legal frameworks, security principles throughout the HMIs technical development and solution deployment.	Tech developers and Manufacturers, Tech providers; Legislation, security and/or privacy experts.	Concept design, development & deployment.	Reduces legal and security risks, improving regulatory compliance and system resilience.
7.2	G7	Map and identify the applicable AI ethical principles and legal frameworks for each phase of the R&D process to which they are relevant.	Tech developers and Manufacturers, Tech providers; Legislation, security and/or privacy experts.	Concept design, development & deployment.	Ensures systems meet evolving legal/ethical requirements, avoiding compliance gaps.
7.3	G7	Utilize ethics-by-design methodologies, including comprehensive and iterative ethical impact assessments	Tech developers and Manufacturers, Tech providers; Legislation, security and/or privacy experts.	Concept design, development & deployment.	Minimizes ethical risks and enhances public trust through built-in ethical safeguards.

7.4	G7	Utilize security-by-design and security-by-default methodologies by identifying and implementing appropriate measures to manage risks to network security and information systems.	Tech developers and Manufacturers, Tech providers; Legislation, security and/or privacy experts.	All phases	Improves system resilience against cyber threats and data breaches.
7.5	G7	Consult with legal experts to ensure compliance with all relevant regulations and standards, conduct regular audits to maintain compliance.	Tech developers and Manufacturers, Tech providers; Legislation, security and/or privacy experts.	All phases	Maintains long-term compliance and system integrity through continuous legal oversight.
7.6	G7	Make suggestions that require changes to legislation based on validation phases and conclusions.	Tech developers and Manufacturers, Tech providers; Legislation, security and/or privacy experts; Policymakers	Validation & policymaking	Aligns legislation with real-world needs, facilitating smoother system rollout and acceptance.
8.1	G8	Engage citizens early and continuously in the development process to ensure the technology aligns with real societal needs and values.	Tech developers and Manufacturers, Tech providers; Scientific Community	All phases	Ensures technology addresses societal needs, increasing acceptance and relevance.
8.2	G8	Ensure transparent communication about HMI system capabilities, limitations, benefits, and risks, to build public trust and informed consent.	Tech providers & Public Authorities.	Deployment & exploitation	Builds public trust and informed adoption by clarifying benefits and limitations.
8.3	G8	Systematically assess the ethical, legal, and social implications of HMI deployment to anticipate societal concerns and avoid unintended consequences.	Tech developers and Manufacturers, Tech providers; Legislation, security and/or	Validation & piloting; Policymaking	Anticipates and mitigates societal risks, ensuring responsible deployment.

			privacy experts; Policymakers		
8.4	G8	Prepare demonstrations in real traffic environments to showcase benefits, gather feedback for the public, and promote societal acceptance through visibility and dialogue.	Tech developers and Manufacturers, Tech providers; Scientific Community; General Public.	Piloting, deployment & exploitation	Increases societal acceptance and adoption through visibility and real-world demonstrations.

Table 4-2: Best practices to implement guidelines and their impact in development and implementation of HMIs.

5. Conclusions

The present document reports the lessons learnt, and insight gathered throughout HEIDI activities to produce practical guidelines for those developing, implementing, and exploiting HMI systems on road-going vehicles for cooperative interaction with pedestrians and other road users, also contributing to best conceptualization, design, development and validation practices. The information collected was structured into eight guidelines and implemented by the formulation of best practices targeted to different profiles. Project partners have been engaged across various phases of the project lifecycle, collaborating across work packages and participating in surveys and workshops providing their experiences, conclusions, lessons, etc.

To enhance usability, specific best practices have been developed to support stakeholders in effectively applying each guideline throughout the R&D process. Each best practice is aligned with the most appropriate phase of the R&D lifecycle and assigned to the stakeholders best positioned to implement it. Two tables providing a summary of the best practices and their corresponding related guideline and their impact in the development and implementation of HMIs are presented as a valuable outcome from the HEIDI project through this deliverable.

Ensuring a safety, inclusive, and effective deployment of HMIs in road transport systems, it is imperative to embed these guidelines and best practices into both technological development and regulatory frameworks from the earliest stages. Policymakers, standardization bodies, and industry stakeholders must work collaboratively to establish harmonized standards that guarantee consistency, interoperability, and accessibility across all vehicle manufacturers and user groups. Integrating iterative validation, ethical and legal safeguards, and citizen engagement into the R&D process will not only enhance system reliability and societal acceptance but also align emerging technologies with fundamental public interests and values. A joint, cross-sectoral effort is essential to create a cohesive regulatory landscape that anticipates future challenges, supports innovation, and safeguards public trust in automated and connected mobility solutions.

6. Abbreviations

Term	Definition
eHMI	External Human Machine Interfaces
HEIDI	Holistic and adaptivE Interface Design for human-technology Interactions
HMI	Human Machine Interfaces
iHMIs	Internal Human Machine Interfaces
IT	Information Technology
KPI	Key Performance Indicators
R&D	Research and Development
UI	User Interface
WP	Work Package

A. Annex I - HEIDI Guidelines and Best Practices questionnaire

Introduction

The following questionnaire is part of the activities defined in HEIDI's WP5 - Validation Methods & Standardization Recommendations under task *T5.5 Recommendations for Legal Framework and Standardisation*. **The objective** is to collect and summarize the best practices and recommendations after the execution of project activities under the design, test and validation tasks. The information collected through this questionnaire will be organized and discussed with all the partners in a workshop previous the delivery of the deliverable *"Best practices for design and development of HMI systems"* (D5.5), where the results of this work will be presented.

Instructions

The questionnaire is structured as follows:

- **Part 1** of the questionnaire is designed to identify the most significant lessons you have learnt, the challenges you have encountered, and the insights and recommendations that have emerged from them.
- **Part 2** outlines the key guidelines derived from the deliverables produced during the design, testing, and validation phases of the HEIDI project. It seeks your input on the most important and least important guidelines, as well as any additional guideline for those involved in developing, implementing, and promoting HMIs on road-going vehicles for cooperative interaction with pedestrians and other road users. It also provides a check table to collect your opinion on how HEIDI meets these guideline, main obstacles, and their implementation.
- **Part 3** is devoted to gather ideas and opinions from partners about the way to implement each guideline. **This part will be discussed as a brainstorming session during the workshop**.

Please answer the questions in each part thinking always on the work carried out during the HEIDI project and the lessons learnt, most importantly, to provide recommendations to future technology developers and manufacturers, technology providers, policymakers or other key stakeholders during the lifecycle of the design and development of HMI systems.

PART 1 - General questions

Q1. In your opinion, what have been the biggest lessons you have learnt throughout the work carried out in HEIDI?

Q2. What were the biggest challenges you faced?

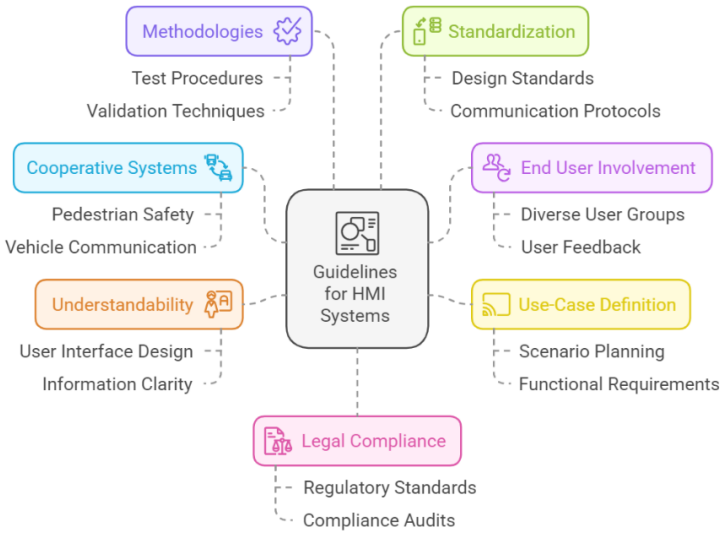
Q3. Based on lessons learnt and challenges, what recommendations would you give to future technology developers and manufacturers, technology providers, policymakers or other key stakeholders during the lifecycle of the design and development of HMI systems?

PART 2 - Guideline questions

The following guidelines, collected from HEIDI deliverables, activities and conclusions, are represented as "themes" in which diverse best practices will be provided.

In this part, the idea is to focus on the guidelines and collect your opinion on the most relevant and lest relevant ones, as well as to know if there is any other additional guideline that is not mentioned.

- **Guideline 1**: Address impacts of cooperative HMI systems for pedestrian-vehicle interactions.
- **Guideline 2**: Involve end users and be sensitive to diversity.
- **Guideline 3**: Define relevant use-cases.
- **Guideline 4**: Be understandable and accessible.
- **Guideline 5**: Comprehensive methodologies, validations and evaluation tests.
- **Guideline 6**: Standardize HMI designs and communication protocols.
- **Guideline 7**: Ensure legal compliance.



Looking at all of the guidelines, please answer the following questions:

Q4. Which of the guidelines do you think are most important when developing, implementing, and promoting HMIs on a roadgoing vehicle for cooperative interaction with pedestrians and other road vehicles?

Q5. Which do you think are the least important?

Q6. Are there any other guidelines you think are missing that are important for those developing, implementing, and promoting HMIs on a roadgoing vehicle for cooperative interaction with pedestrians and other road vehicles?

Looking at each of the guidelines individually, please answer the following questions:

Q7. Do you think the HEIDI eHMI, iHMI and cooperative HMI meet this guideline? Why/Why not?

Guideline	Yes/No	Why not?
nº 1		
nº 2		
nº 3		
nº 4		
nº 5		
nº 6		
nº 7		

Q8. Are there any specific obstacles to implement this guideline? How do you think these could be overcome in future projects?

Guideline	Yes/No	How could be overcome?
nº 1		
nº 2		
nº 3		
nº 4		
nº 5		
nº 6		
nº 7		

Q9. How would you think this guideline could be best implemented?

Guideline	How could be best implemented?
nº 1	
nº 2	
nº 3	
nº 4	
nº 5	
nº 6	
nº 7	

PART 3 - Best practices used as prompts - workshop

This part will be discussed as a brainstorming session during the workshop.

Looking at each of the guidelines individually, please answer the following questions:

Q10. Do you think this is a suitable way to implement guideline x? Why/Why not? Is there a more effective way of implementing this guideline?

Q11. Are there any best practice recommendations missing here?

Q12. Which of these best practices do you think is the most effective/least effective?

Q13. Which of these best practices do you think is the easiest to implement/hardest to implement?