Cooperative HMI Concept

Deliverable Number	D4.2
Deliverable Type	R – Document, Report
Dissemination Level	PU (Public)
Authors	Nikolai Ebinger, Paolo Pretto / VIF
Document Version & Status	V2.0 | Final

Project Acronym	HEIDI
Project Title	Holistic and adaptivE Interface Design for human-technology Interactions
Grant Agreement Number	101069538
Project Coordinator	Virtual Vehicle Research GmbH
Project Website	https://www.heidi-project.eu

HEIDI has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No. 101069538.

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Change History

Version	Date	Name/Organisation	Description
0.1	2023-07-05	Nikolai Ebinger (VIF)	Initial Draft created
0.2	2023-07-06	Miguel Ángel (UAH)	Edit 5. Situation Resolution Tracking
0.3	2023-07-12	Michael Brunner, Markus Rehmann (RUAS)	Edit 3.2 External HMI logic
0.4	2023-07-24	Markus Amann (HRI-EU)	Edit for 3.3 Cooperative HMI
0.5	2023-07-27	Nikolai Ebinger (VIF)	Description of the relation between the HMI logics (4.1)
1.0	2023-08-02	Paolo Pretto (VIF)	Final Draft created
2.0	2023-08-30	Paolo Pretto, Nikolai Ebinger (VIF)	Final version created

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1. Executive Summary

This HEIDI project deliverable outlines the underlying concept of the HEIDI cooperative human machine interface (HMI). This deliverable primarily builds upon the work on user needs described in D1.1 and the use cases defined in D1.2. At the same time, the HMI logics described provide the basis for the HMI design which will be elaborated in D3.2 and D4.2. This deliverable provides an internal and external HMI logic which determine the intern- and extern HMI actions. The internal HMI logic describes the interaction with pedestrians in a way that aims at supporting the driver in the best possible way. Similarly, the external HMI logics aims to primarily support pedestrians based on their needs in situations in which they must interact with cars. Both decision logics will be applied in the initial HMI design and the explorative studies. The learnings will be used to define the final cooperative HMI logic – an initial version of this HMI logic (with focus on the cooperation between drivers and pedestrians) is presented in this deliverable. The HMI logics receive their input from sensing and the recommended behaviour optimization. The behaviour optimization serves as the basis to propose a resolution of possibly conflicting pedestrian crossing situations. An additional situation resolution tracking becomes relevant in the cooperative HMI logic. The initial concept of the recommended behaviour optimization and the situation resolution tracking is outlined in this deliverable. The work presented in this deliverable is a central step within the HEIDI project as it provides the basis of the internal- and external HMI and outlines the cooperation concept.

Keywords: Cooperative HMI, External HMI, Internal HMI, Automated Driving, Pedestrian Crossing

2. Objectives and general structure

The objective of this deliverable is to provide an overview of the HEIDI cooperative human machine interface (HMI) concept. The developed concept builds upon the use cases and sequence diagrams described in D1.2. The aim was to identify and predict potential interactions between an ego-vehicle and other road users, with the goal to optimize these interactions in terms of safety, efficiency, and comfort. We incorporate two parallel HMI logics that are the rationale behind the internal and external HMI. These logics and the resulting internal- and external HMIs will be individually researched in explorative studies. Learnings from these studies will then be incorporated into a combined cooperative HMI logic which will be the basis for the combined implementation of internal- and external HMI. An initial version of the cooperative HMI logic which outlines the behaviour coordination between driver and pedestrian is presented in this deliverable. A significant input for all HMI logics described is, besides sensing, the recommended behaviour optimization. The concept and reasoning behind those recommendations is described in chapter “5. Recommended Behaviour Optimization”. An additional situation resolution tracking is relevant for the cooperative HMI logic and is presented in chapter “6. Situation Resolution Tracking”.

Initially three HMI logics are developed to serve the three HEIDI core aspects: driver, pedestrians, and cooperation in the best possible way. Developing individual logics for internal HMI and external HMI ensures that the driver and pedestrian perspective are equally considered. The internal HMI logic addresses the cooperation that serves the driver needs and the external HMI logic addresses the cooperation in a way that serves the needs of the pedestrians. In contrast, the cooperative HMI logic takes a neutral perspective with focus on improving the cooperation. Due to the overlapping aims, the three HMI logics include overlapping elements. However, this is not a problem as the findings from researching the internal- and external HMI individually will be used to enrich the cooperative HMI logic and to implement the HEIDI HMI holistically. Section 3 provides the background information and general principles from which the detail HMI concepts were derived. Section 4 provides and overview of the HMI logics that define the internal-, external-, and cooperative HMI which use the recommendation of optimized joint behaviour.

The recommended behaviour optimization is developed in T4.4. While the task is still ongoing, the initial concept is outlined in “5. Recommended Behaviour Optimization”. The behaviour optimization builds upon [1]. Within the behaviour planning, the system predicts intention-based trajectories for other interaction partners. Sensed information about the state of the other interaction partner as well as path relations relative to the ego-vehicle allow to make inference about the intention of the interaction partner. Similar to [2] two different options for the intended situation resolution by other road users are considered in the prediction. These options differ regarding the outcome of the situation (e.g., other traffic participant passes a shared space before the ego-vehicle, or ego-vehicle goes first, and the other second). Subsequently, the ego behaviour is optimized for each of the prediction options with respect to quality criteria such as risk, utility and comfort. The recommended behaviour is passed to the HMI logics. The HMI logics process the recommendation together with sensing data. The cooperative HMI logic also receives information and knowledge about implications of communication and information about previous communication cues. The presented recommended behaviour optimization concept will be applied, evaluated, and further iterated in the following period of T4.4.

In addition, the HMI output will be modulated based on the accordance of ego-driver and outside traffic participant behaviour with the communicated recommendations. An overview of this concept will be provided in “6. Situation Resolution Tracking”, covering the ideas that will be implemented in T4.5.

The work described in this deliverable will provide the basis for the communication signal selection planned in T4.6. That task will develop a module which determines the communication of the internal and external HMI. Furthermore, the expected effect of the communication on the interaction partners will be modelled. An infrastructure for data synchronisation will ensure the consistency between internal- and external HMI.

Overall, this deliverable addresses the HEIDI project objectives 1 and 2. HEIDI objective 1 aims at developing and demonstrating fluid, cooperative HMI solutions. The work described in this deliverable provides the basis for the fluid and cooperative HMIs. Here, especially the cooperative HMI logic and the recommended behaviour optimization provide the fundament for creating cooperation through the HEIDI HMI. HEIDI objective 2 aims at developing technical innovation modules for mutual awareness between road users and drivers. The underlying methods for displaying information to all traffic participants involved, the recommended behaviour optimization, and the situation resolution tracking provide the basis to develop HMIs that improve the mutual awareness between road users and drivers.

3. Inspiring principles of HEIDI fluid, cooperative interface

The HEIDI holistic approach is inspired by the fluid interaction concept [3]. However, HEIDI further expands the fluid concept connecting internal and external HMI and enabling the cooperation between driver, vehicle and pedestrians through the HMI logics, which are informed by the recommended behaviour optimization and situation resolution tracking. Fluid, indeed, as a metaphor for continuous and seamless interactions, can be expanded to include the outside of the vehicles as part of a unified interaction and communication system.

However, the HEIDI cooperative interface is not a collection of systems, covering specific topics like, e.g., driver monitoring on the inside and pedestrian detection on the outside, and working in a parallel and independent way. Instead, we are creating a system of systems, that covers the gaps in between and provides continuity for the solutions with no separation between in- and outside. This approach accounts for situations that are non-standard and complex, in other words, close to real-life (Figure 3–1).

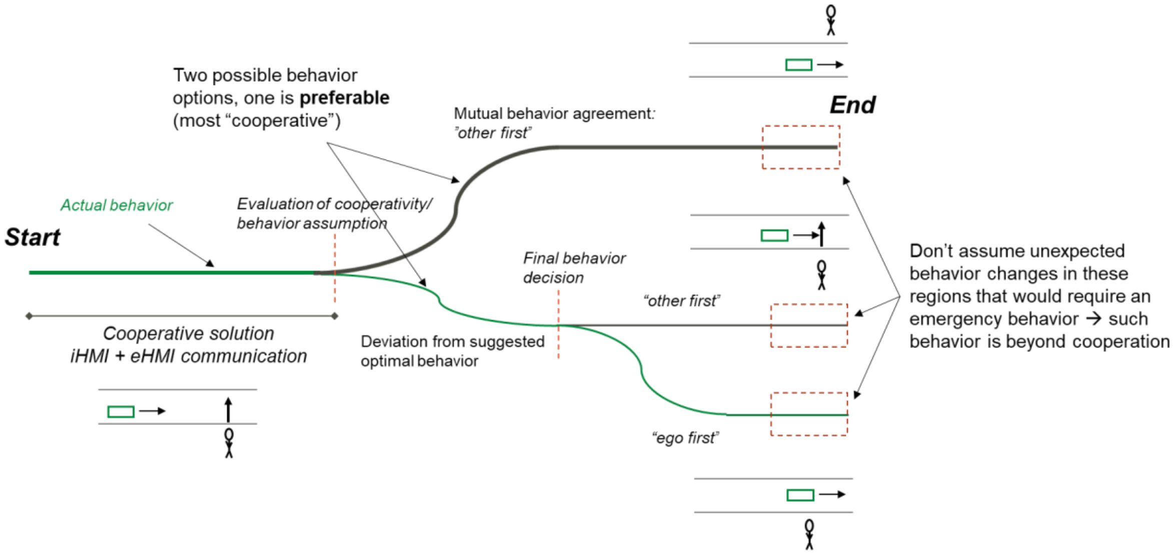

Figure 3–1: Vehicle-pedestrian interaction possibilities

To cover the different vehicle-pedestrian interaction possibilities, HEIDI use cases (Deliverable 1.2) were selected and developed to allow some (or all) players to decide whether they want to adhere to the suggested situation resolution or not. So, like a fluid, we aim at covering all the gaps and spaces, to provide continuity and support for situations with multiple players, and players with multiple intentions, even changing over time. The cooperative HMI logic, therefore, has the role of integrating, coordinating, matching the communication of recognized states and intentions to the mutual agents engaged in interaction, within a complex and variable context.

Finally, another aspect of the fluid metaphor that is explored in the HEIDI project concerns the avoidance of sudden changes, rather focusing on a gradual adaptation of the communication and interaction to evolving situations. The communication way, depending on situation, driver type and driver state, is integrated within the processes of the HMI logics and thus will reflect the individual HMI designs.

4. HMI logics

HMI logics serve as schematic description of the processes behind the HEIDI internal and external HMIs. The HMI logics are the binding elements that merge information from in-vehicle, including information on the driver, and outside sensing to trigger respective HMI actions. We refer to HMI actions as everything the HMI communicates e.g., via light or display indication. While the HMI design itself is a separate task (internal HMI design in D2.1 and external HMI design in D3.1), the HMI logic provides the reasoning for each HMI action required in each situation as described in D1.2.

The HEIDI HMI logics are designed to serve all situations and users type and current state within the HEIDI scope. The HMI logics were developed upon the user needs defined in D1.1 and the use cases identified and presented in D1.2. While the sequence diagrams provided in D1.2 gave an initial overview on what information needs to be presented to whom in which situation, the HMI logics describe the specific HMI actions required in each situation for the internal- and external HMI. To research the internal- and external HMI in the explorative studies, an internal HMI, and an external HMI were developed.

An initial separate internal and external HMI logic were developed to identify and research the needs of drivers and pedestrians. The resulting decision logics show differences, as the needs and perspective differ, and overlapping aspect as both aim at improving the same situations. For example, the internal HMI logic needs to provide information to the driver already ahead of the interaction situation as the driver needs to be aware about upcoming crosswalks or possibly hidden pedestrians. In contrast, information on the external HMI is only presented to pedestrians in situations of interaction. This is due to its fundamental nature as the external HMI on a car displayed messages are only visible to pedestrians if the car is close enough. An example for an overlap is an HMI escalation based on the time to collision (TTC) between car and pedestrian which is present in both HMI logics. For the iHMI logics, the TTCs vary between different driver types and states. The related HMIs will be researched in explorative studies to further improve the way drivers and pedestrians are supported.

The learnings from researching internal and external HMIs will be used for finalizing the cooperative HMI logic. The cooperative HMI logic will replace the internal and external HMI logics for future HEIDI HMI implementations that consist of both, internal- and external HMI. Within this section, the initial cooperative HMI logic is presented to outline how it triggers HMI actions to both, internal- and external HMI, in order to improve the cooperation between driver and pedestrian. This initial cooperative HMI logic will be enriched – for the combined HEIDI HMI implementation – by aspects currently only described in the internal- or external HMI logic. However, this was not done yet as the upcoming explorative HMI studies will first evaluate the HMI and its underlying logic. Then, using these findings, aspects from the individual HMI logics will be considered for the final cooperative HMI logic.

Generally, the HMI logics operate as a loop that runs during the operation of the ego-vehicle. This uses the input of sensing, recommended behaviour optimization, and situation resolution tracking to determine the displaying of information. Figure 4–1: Overall HMI decision logic process shows sensing input, recommended behaviour optimization, situation resolution tracking, HMI logic, and HMI display. The logic within “Sensing” module is outlined on the right side. This loop lets the HMIs react to the dynamically changing internal and external conditions, potentially even considering previous communication states.

The sensing module consists of internal (driver) sensing and external (pedestrian / environment) sensing. Both submodules generate different sensing data which needs to be merged into the overall sensing output of the module. The sensing output is then delivered to the HMI logics. The HMI logic then determines what the internal and external HMIs display. Furthermore, this structure allows for separate implementation and testing due to a high abstraction level.

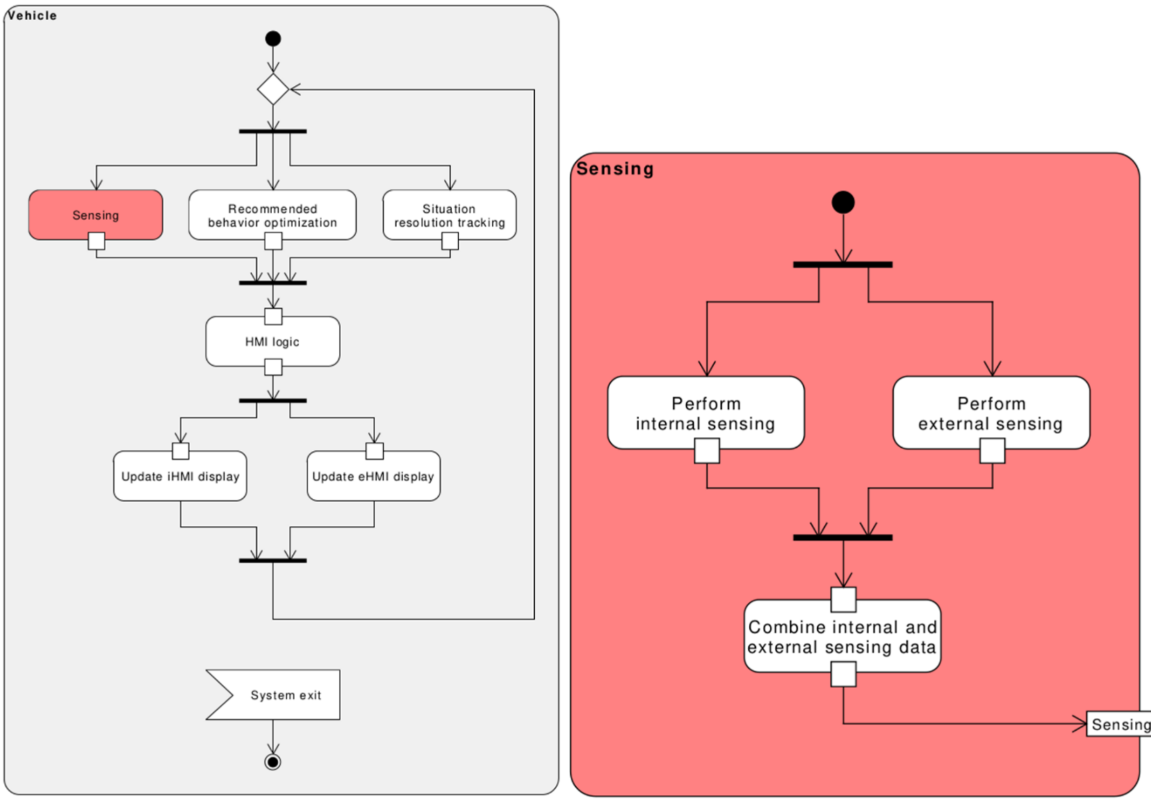

Figure 4–1: Overall HMI decision logic process

A recent work emphasizes the need for standardized and consistent ways of providing vehicle status and alerts to drivers [4]. By drawing inspiration from the established alert management structure in aviation, the paper introduces a taxonomy of vehicle display status and alerting terminology with the aim of creating a managed display system. Within HEIDI, we adapted the alerting terminology for the different actions of the HMIs. The used types of HMI action levels of alertness differ in their saliency and the way where and how information is presented. How each individual level is displayed depends on the driver type and state. For regular drivers, “Level 1: inform” informs drivers about a situation in a more silent way. “Level 2: Warning” increases the saliency, as it aims to warn drivers about a situation and explicitly attract their attention. “Level 3: Alert” is defined as alert and is used in urgent situations that require an immediate action by the driver. The maximum “Level 4: Emergency” is only used in emergency situations that trigger a reaction by the vehicle driving emergency systems like, e.g., an emergency brake.

4.1 Internal HMI logic

The internal HMI logics define what the iHMI will display in each of the situations defined in the use case descriptions in D1.2. The flowcharts (Figures 4-2 through 4-4) describe a continuous stream of checking for the current situation and resulting HMI actions for regular, older and distracted drives, respectively. Black circle signifies an endpoint requiring no further actions, while black bars consolidate multiple input arrows into one.

4.1.1 iHMI logic for regular drivers

The process, entirely depicted in Figure 4–2: Decision logic of Internal HMI for regular drivers, starts with external information from a database that provides the driver's age and information about crosswalk locations. In addition, internal and external sensing is used. Depending on the TTC with a crosswalk, the HMI displays information about its occurrence. This type of information is of low urgency and therefore triggers a “Level 1: Inform” HMI action. Depending on the situation and the number of times this type of information has been presented, a “Level 2: Warning” HMI action is triggered. If no pedestrians are present, the HMI logic will not start any further HMI actions. If one or more pedestrians are present, information from the sensing and recommended behaviour optimization logic is used to provide the driver with information about the pedestrian's location and recommended behaviour (both “Level 1: inform” HMI actions). In case the driver does not see the pedestrian, a warning HMI “Level 2: Warning” action is triggered.

If the ego-vehicle approaches the pedestrian, a two-step escalation within the internal HMI logics is activated. If the TTC is less than nine seconds, the driver receives a “Level 3: Alert” HMI action. If the TTC is equal to or less than two seconds, a “Level 4: Emergency” HMI action with emergency braking is triggered. The TTC values are derived from scientific literature [10], but are subject to change according to results of the explorative studies.

Depending on the driver type and driver state, modified versions of the HMI logic become active. Unlike age, driver state can change continuously, so a driver may start driving and the normal driver HMI logic is active, but later in the trip the distracted driver HMI logic is needed and is active.

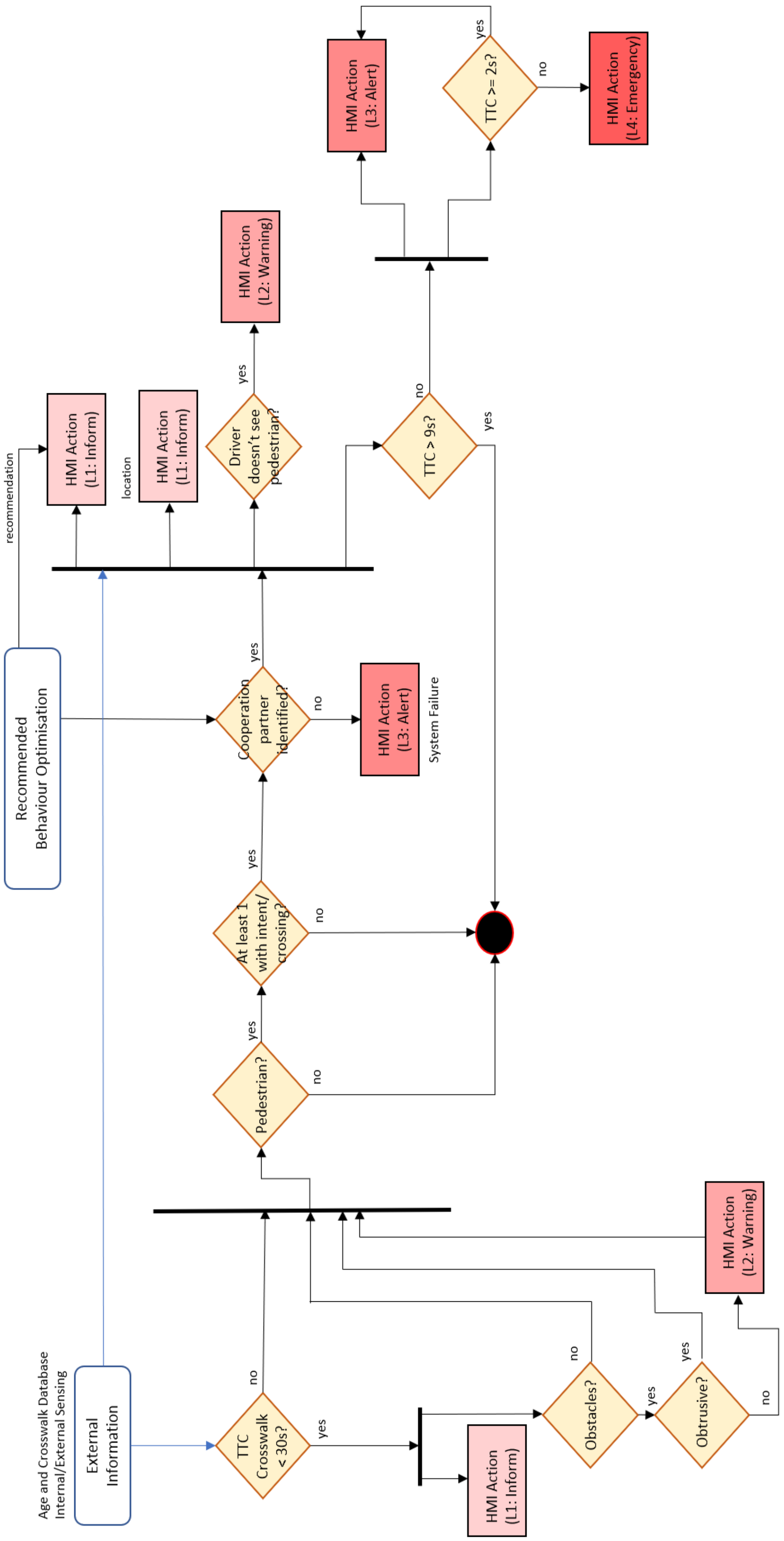

Figure 4–2: Decision logic of Internal HMI for regular drivers

4.1.2 iHMI logic for older drivers

The internal HMI displayed to older drivers (defined in D1.1) is informed by a slightly adapted HMI logic (Figure 4–3). For older drivers, the logic of four separated levels of HMI actions remains the same, but the HMI implementation is adapted to the needs of older drivers. The specific HMI design will be presented in D2.1. The changed HMI interpretation of HMI actions is indicated by a plus added to each level (e.g., Level 1+ instead of Level 1). Besides adapted HMI design, older drivers receive additional information as soon as a pedestrian's intention to cross is detected. In comparison, regular drivers receive that information only when the location and recommendation are updated. This change in comparison to the regular driver HMI logic was made to serve the need of older drivers to have extended time to react to situations (as identified in D1.1). Therefore, the HMI logic for older drivers has adapted HMI Actions levels with a faster escalation than the HMI logic for regular drivers. In addition, it includes an additional HMI action for informing the older ego-driver about pedestrians.

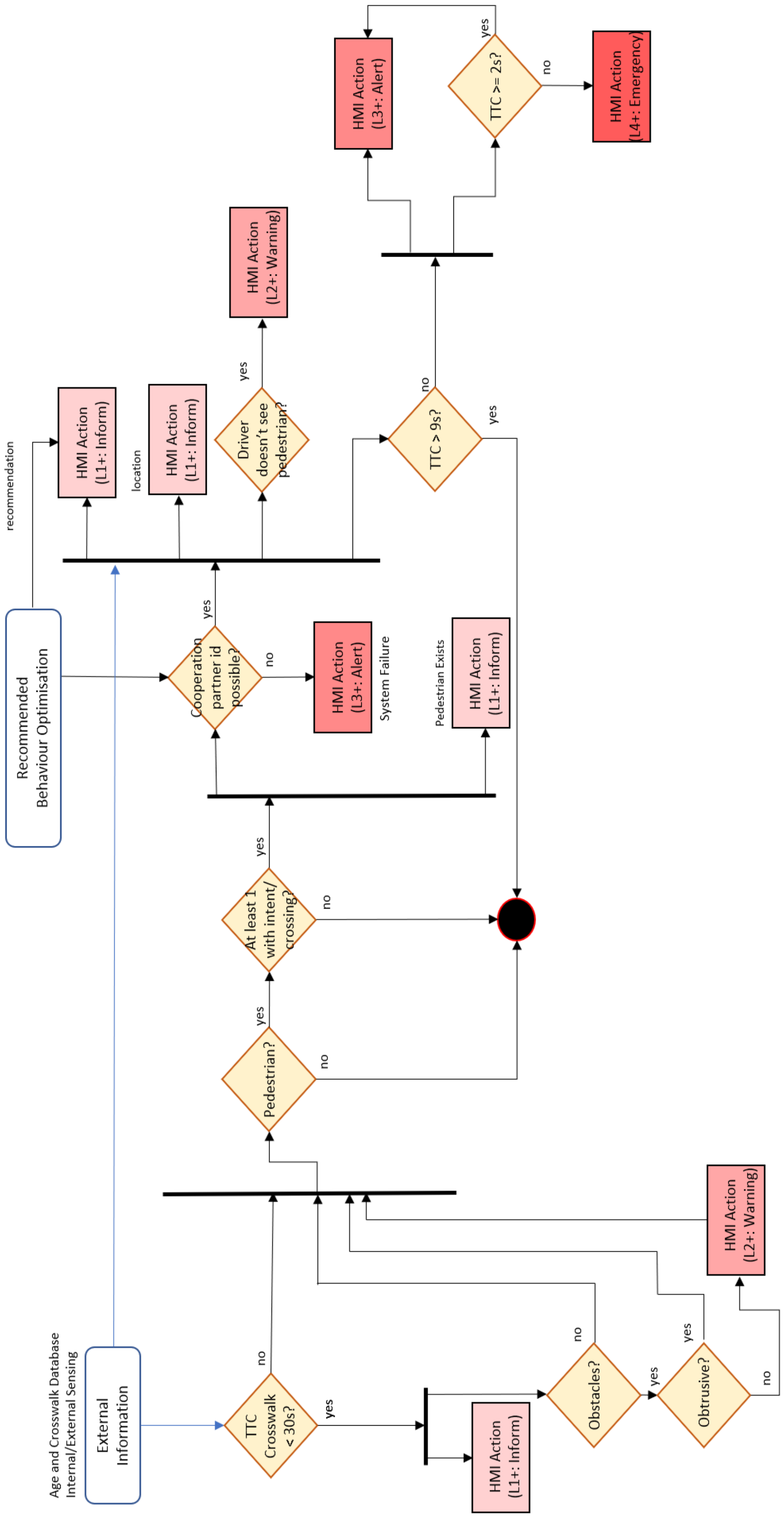

Figure 4–3: Decision logic of Internal HMI for older drivers

4.1.3 iHMI logic for distracted drivers

The state of drivers can change at any time to distracted, in that case the internal HMI logic switches to the version for distracted drivers (see Figure 4–4). Similar as for older drivers, the HMI logic for distracted driver builds upon the regular one but comes with adaptations to better serve the needs of distracted drivers (as defined in D1.1). While the HMI Action levels remain the same for each HMI Action, the actions for distracted drivers are marked with an asterisk. The asterisk indicated that the HMI design for those actions differ from the regular ones. For example, the infotainment screen will be used to bring the attention back to the driving situation in a fluid manner. In addition, the escalation for short TTCs will be changed with having earlier escalations. In general, this version of the iHMI has adapted HMI Actions levels with an earlier activation and with a faster escalation than the HMI logic for regular drivers.

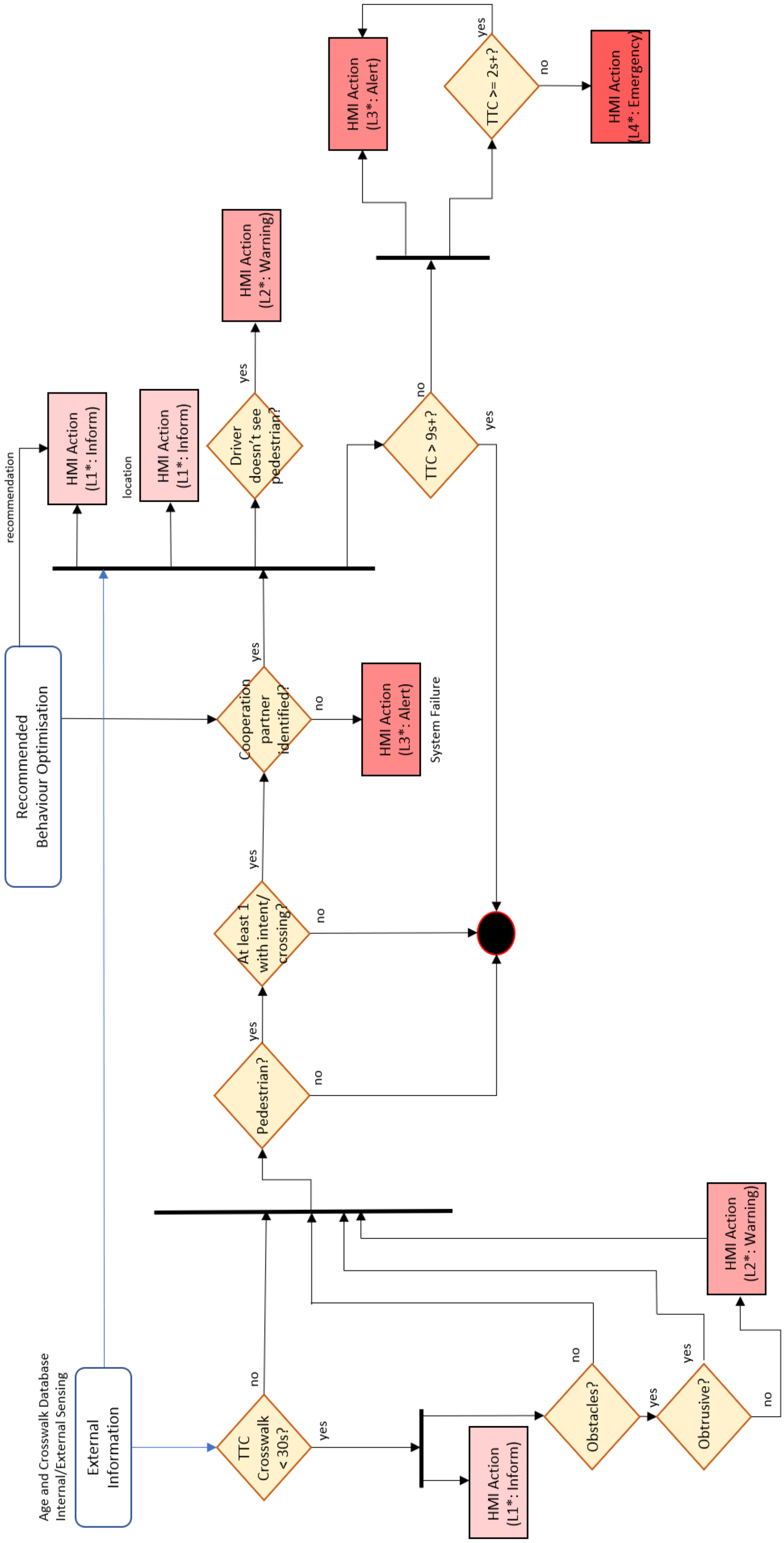

Figure 4–4: Decision logic of Internal HMI for distracted drivers

4.2 External HMI logic

The focus of this chapter is the external HMI logic with the aim on supporting the pedestrian. Herby, besides considering all use cases described in D1.2, a special focus lies on use case 2. The external HMI logic is shown in Figure 4–5. Especially the external sensing data is considered in this module, which contains information about pedestrian action and type for every detected pedestrian.

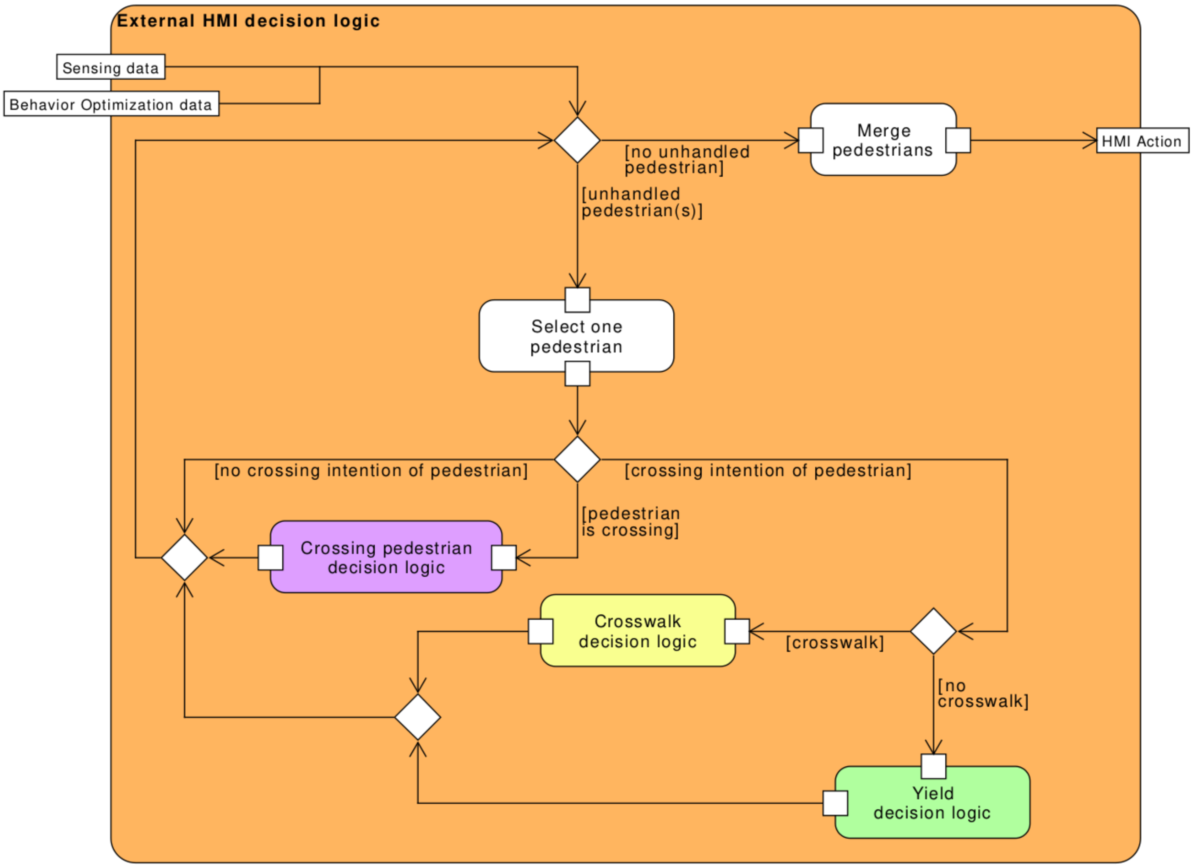

Figure 4–5: Decision logic of external HMI

A loop occurs in the module which is repeated for every detected pedestrian. The status of the pedestrian's crossing action is considered and handled accordingly.

- If the pedestrian has no intention to cross, he/she can be ignored.
- If the pedestrian is not crossing (yet) but has the intention to cross, a further distinction needs to be made.
    - If the pedestrian is at a crosswalk, the crosswalk decision logic is executed (see Figure 4–6).
    - Without a crosswalk, the yield decision logic is applicable (see Figure 4–7).
- If the pedestrian is already crossing, the ego-vehicle needs to wait for the pedestrian to finish. The HMI information is then decided according to the crossing pedestrian decision logic, see Figure 4–8.

The information about all detected pedestrians is merged into a unified HMI action.

4.2.1 Crosswalk decision logic

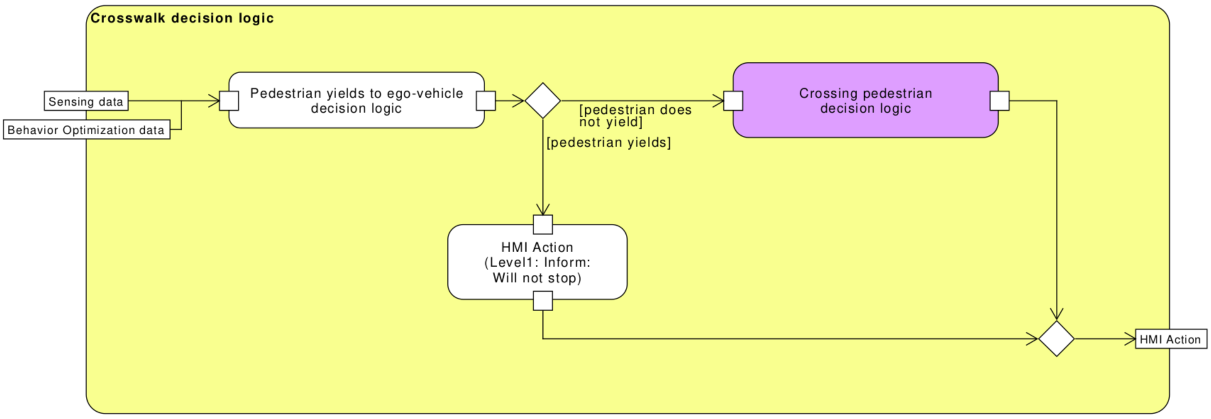

Figure 4–6: Decision logic for crosswalk interaction between ego-vehicle and pedestrian(s)

In the crosswalk decision logic, even though from theoretical perspective pedestrians always have priority, they can still decide to yield. Thus, the sensing data is checked to see if the pedestrian is yielding to the ego-vehicle. If that is not the case, the logic moves to the crossing pedestrian decision logic, see Figure 4–8. Otherwise, the ego-vehicle will not stop and an HMI action is triggered to acknowledge the yielding pedestrian.

4.2.2 Yield decision logic

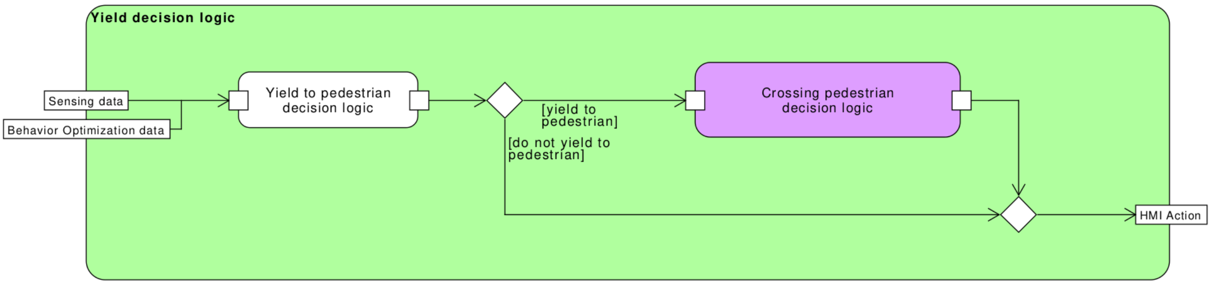

Figure 4–7: Decision logic when yielding to pedestrian(s)

The yield decision logic evaluates the parameters in the sensing data to determine if the ego-car should yield to the pedestrian. When yielding to the pedestrian the crossing pedestrian logic takes effect, see Figure 4–8.

4.2.3 Crossing pedestrian decision logic

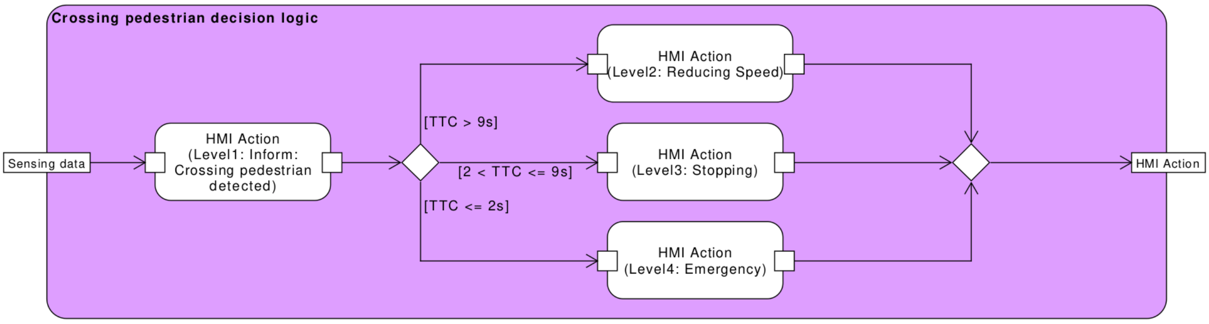

Figure 4–8: Decision logic for crossing pedestrian(s)

To indicate that the pedestrian has been recognized and the ego-vehicle will wait for the pedestrian an internal and external HMI information needs to be triggered. The purpose of the internal message is to inform the driver in case the pedestrian was not seen. And the external message will inform the pedestrian that he/she was recognized. The TTC determines the severity of reaction of the ego-vehicle. The TTC values are placeholders as of now and will be evaluated in the preliminary simulator studies. Dependant on the TTC value three different actions can be envisioned. First, for uncritical situations just a warning is displayed that the ego-vehicle is reducing speed. For situations where a collision could occur the ego-vehicle displays a more urgent warning. For situations, where the stopping of the ego-vehicle is required in any case, the ego-vehicle indicates that it will initiate a stopping manoeuvre. This detailed information system is supposed to build trust and encourage quicker actions of the pedestrian due to mutually shared information about the current situation and future actions.

4.3 Cooperative HMI logic

The logic of the cooperative HMI (cHMI) is the overarching logic of a combined implementation of internal- and external HMI. This section provides the initial cooperative HMI logic with the aim of improving driver-pedestrian interaction. The HMI logic presented in this deliverable will be iterated after the explorative studies on the internal- and external HMI and will be enriched by aspects from the internal- and external HMI logics that have proven to be important throughout the separated exploration.

The presented concept of the cHMI logic is a preliminary approach that mainly focuses on the cooperative aspects between the interaction partners during an interaction. After the exploratory studies for the internal and external HMIs, the cHMI logic will be enriched with the gained knowledge about the respective HMIs and adjusted accordingly. The cooperative HMI triggers coordinated actions of the internal and the external HMI components to ensure communication between both interaction partners. If a coordinated communication through the HMIs is necessary to facilitate cooperative behaviour of the interacting road users, the high-level cHMI logic (see Figure 4–9) activates the cHMI logic. On the one hand, the module transmits behaviour recommendations to the interaction partners via internal and the external HMI actions. On the other hand, the cHMI logic receives information about the recommended behaviour as well as the state of the current situation (e.g., TTC, previous communication, behavioural accordance).

The usage of the information that feeds into the cooperative HMI logic allows for a holistic understanding of how the situation evolves and allows the cHMI logic to output suitable communication signals or adapt them accordingly. The behaviour recommendations that are transmitted from the behaviour optimization to the cHMI contain semantic information about the optimal cooperative behaviour such as the recommended order for passing the traffic space for which the pedestrian shows the intention to cross the road. Additionally, information about the compliance of the respective road users regarding the recommended behaviour is used to modulate the quality and the content of the communicated messages. This helps to increase the transparency of the recommendations as well as the comprehensibility of the system. How the respective information is displayed to the interaction partners is part of WP2 and WP3 in which the actual iHMI and eHMI components will be designed.

4.3.1 High-level cooperative HMI logic

Figure 4–9 depicts the high-level decision logic of the cHMI which activates the cHMI if necessary. The TTC is a relevant measure that determines whether a cooperation is necessary at all or not. Thus, when the TTC is too large the system does not activate the cHMI logic since there is no need for cooperation. Similarly, when the TTC is too small the time margin for cooperation is already over, thus the cHMI logic is not activated. In critical situations there is only time left for emergency maneuvers. The cHMI module runs and updates its recommendations at a frequency of approximately 1-2Hz.

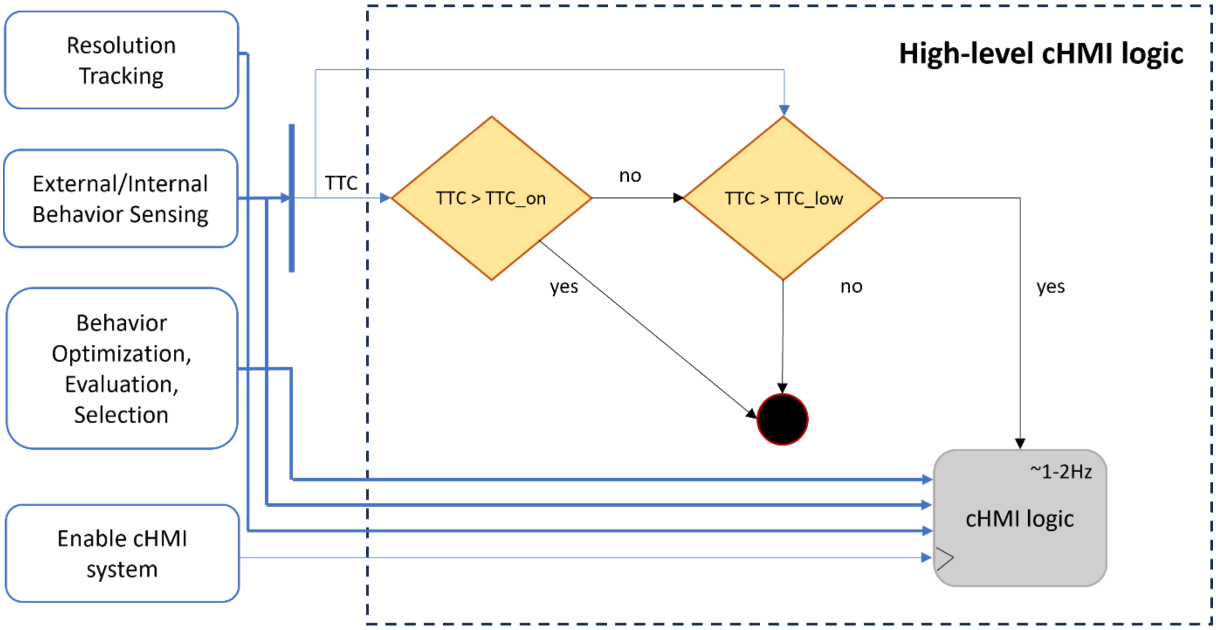

Figure 4–9: High-level decision logic of the cooperative HMI

4.3.2 Submodules of cooperative HMI logic

As depicted in Figure 4–10, the TTC can be split up into three parts: The assumed reaction time of the addressed interaction partner (default value: T_reaction = 1s), the safety margin which needs to be kept for safety reasons (default value: T_safety = 2s) and the time that is left for effectively executing the cooperative behaviour. Thus, the lower threshold TTC_low for a cooperative action is 3 seconds. Assuming that the cooperation partner needs a certain amount of time to react to our communication and at the same time we need to keep the specified safety margin, we disengage the cHMI system for any risky or hazardous behaviour that takes place with TTC < TTC_low because this is beyond the scope of cooperation and requires an emergency reaction, similarly to the logic that is applied to the internal HMI (see section 4.1). The upper threshold TTC_on for which interactions just become relevant for cooperation will be validated during the small-scale simulator studies within WP5. An initial proposal is TTC_on = 20s. This threshold determines the largest TTC for which the cHMI can be turned on. The time used in future iterations will depend on the learnings from the explorative studies as the current internal HMI logic would require the HMI logic to being active at a TTC of 30s to a crosswalk. A third threshold TTC_large is set to 15 seconds. Within TTC_on and TTC_large we assume that interactions are relevant for cooperation, but as the interaction partners are potentially far away from each other, we only use the iHMI interface for the communication. The last threshold TTC_med is set to 9 seconds. This value can be motivated by surveys that study the crossing behaviour of pedestrians during interactions with cars or other motorized vehicles (see Sun et al. (2002), Wang et al. (2010), Giuffrè et al. (2016)). All of the referenced studies come to the result that a time gap of approximately 9 seconds between a pedestrian with a crossing intention and an upcoming vehicle would be accepted by more than 80% of the recorded pedestrians. Figure 4–10 shows the structure of the cHMI logic. The logic receives information from the behaviour optimization module about the recommended behaviour as well as from the resolution tracking whether the interaction partners behave accordingly. The resolution tracking has impact on the urgency level and the content of the communicated messages. Depending on the TTC, the cHMI logic enters one of its submodules. Each submodule receives input about the recommended behaviour from the behaviour optimization module as well as information about the behaviour accordance from the resolution tracking. Additionally, the submodules receive information about previously communicated messages.

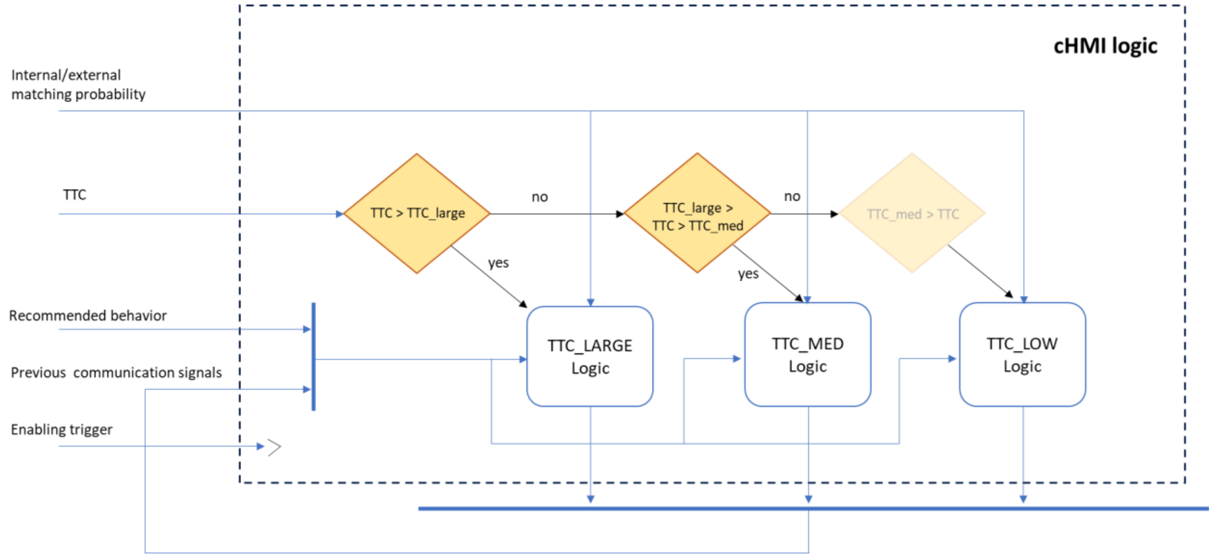

Figure 4–10: cHMI decision logic and submodules

4.3.2.1 Cooperative HMI logic for large TTC

If the system detects a potential interaction partner which is far away, yet relevant for a cooperation (TTC_on > TTC > TTC_large), it enters the TTC_LARGE logic module. Within this submodule we only use the iHMI as the outside road user is still far away and we might confuse other road users by engaging the eHMI. The inner structure of this submodule is shown in Figure 4–11. In the first stage of the TTC_LARGE module we check if the currently perceived driver behaviour is in accordance with the optimal behaviour. If the behaviour matches the recommendation, the iHMI communicates a message of approval to the driver (e.g. “You are doing good, please continue” or a thumbs up symbol). The resolution tracking continuously tracks the driver behaviour and compares the behaviour to the current behaviour recommendation (NOT the previously communicated behaviour, since this can vary in some edge cases when the recommended behaviour switches). In case the driver does not behave compliant with the recommended behaviour an informing message is sent out through the iHMI. This message should at least contain information about the cooperation partner as well as the optimal order of passing (e.g. “There is a pedestrian. Please yield to let him cross the road.”). If the driver adapts his behaviour according to the communicated recommendation and this is sensed in the next cycle of the cooperative system, an approving message is communicated. If the driver does not adapt his behaviour, thus still behaves non-optimal, an additional warning message is communicated. This can imply an audio signal to create awareness towards the iHMI and the cooperation partner or another visual signal such as a coloured element that clarifies the non-compliant behaviour. This cycle can be repeated, and urgency can be further increased until the driver finally adapts his behaviour.

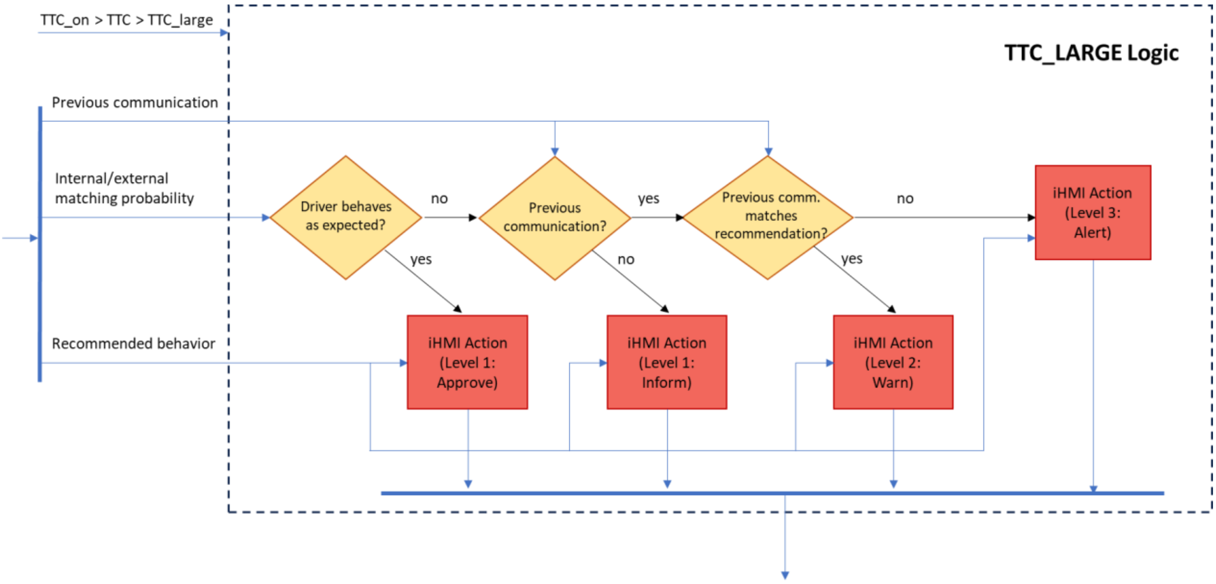

Figure 4–11: Cooperative HMI logic for large TTC

4.3.2.2 Cooperative HMI logic for medium TTC

If the TTC decreases during the interaction such that it becomes smaller than TTC_large, the cHMI logic enters the submodule for TTC_med. The structure of this submodule is depicted in Figure 4–12. The basic functionality is similar to the TTC_large module but instead of only using the internal HMI, now both the iHMI and the eHMI are used to address the driver as well as other road users. The eHMI is used in a similar way as the iHMI with slight differences. The most important difference is that the eHMI only communicates a joint behaviour message to other road users if the driver behaves compliant. If the driver behaviour does not match the recommendation a basic warning signal is displayed to the outside road user to create awareness regarding the ego-vehicle. This message can be a subtle visual message (e.g. light signal or pictogram of a warning sign). As soon as the resolution tracking delivers positive feedback regarding the driver behaviour, the resulting joint behaviour is communicated to the outside road user. From this point on, the logic for the eHMI contains the same functionality as explained already for the internal communication. The external communication will optimally be able to communicate the recommended order of the situation (e.g. “The driver is advised to yield for you in order to let you cross the road.”), rather than a recommended behaviour (“cross the road”), as well as a message of approval for the correct behaviour. Like the internal communication, another auditory or visual warning signal is necessary to increase the level of urgency in case the outside road user does not behave compliant.

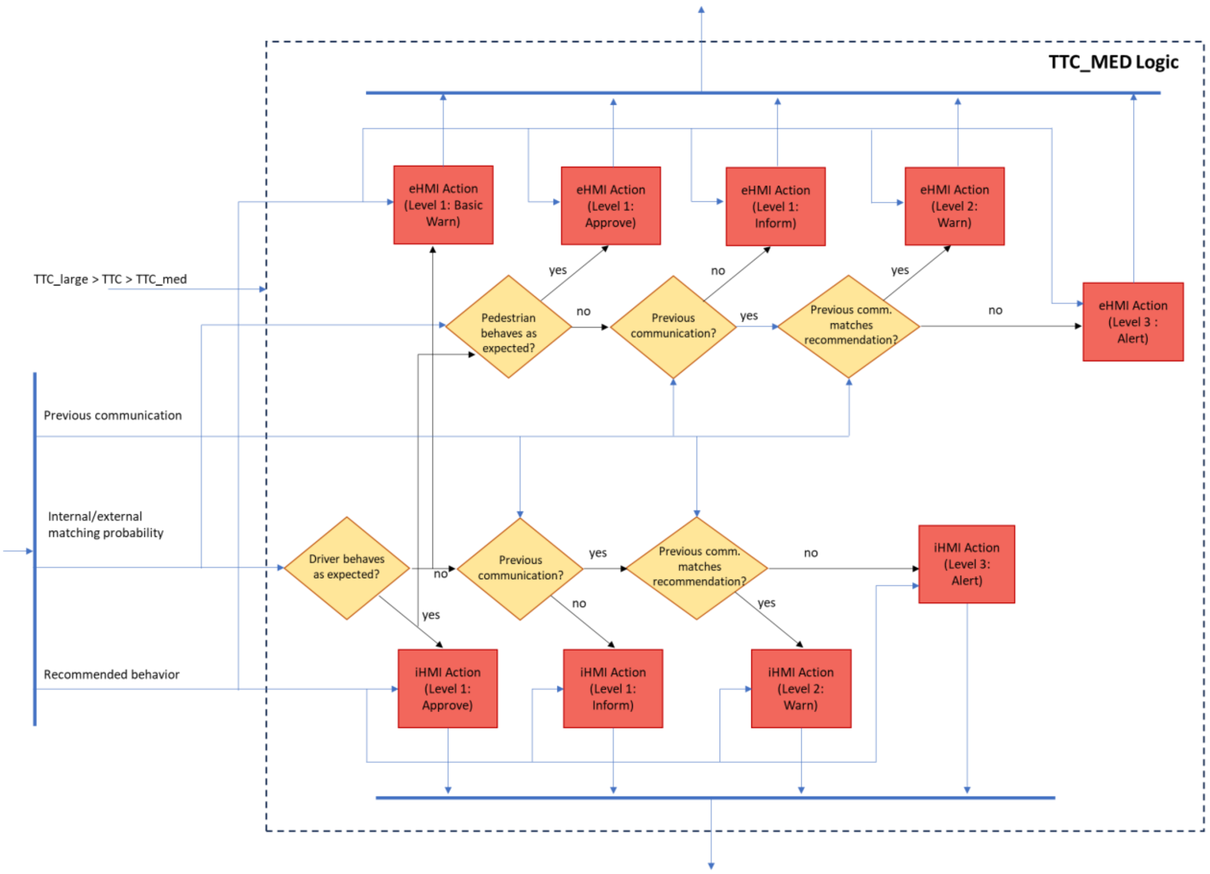

Figure 4–12: Cooperative HMI logic for medium TTC

4.3.2.3 Cooperative HMI logic for small TTC

Finally, if the situation further evolves and the TTC becomes smaller than TTC_med, the system enters the last submodule, which is depicted in Figure 4–13. Similar to the TTC_med module, the external behaviour recommendations will only be sent out if the driver behaves according to the recommendation. In contrast to the TTC_med module however, the TTC_low logic uses higher levels of urgency in earlier stages due to the smaller time that is left for resolution.

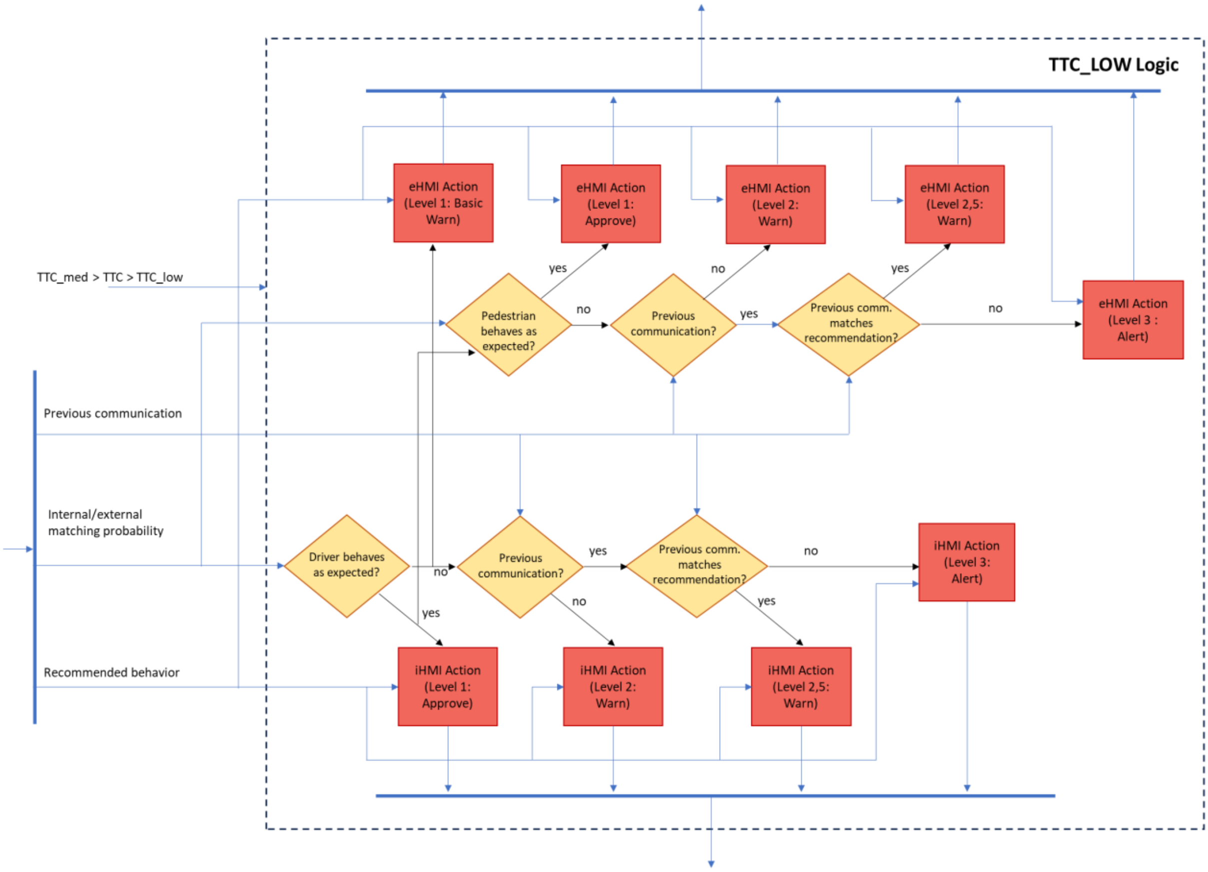

Figure 4–13: Cooperative HMI logic for small TTCs

5. Recommended Behaviour Optimization

5.1 Context

The optimization of the recommended behaviour builds upon the risk-based behaviour planner by [1]. Perception data such as dynamic states of the interaction partners which is provided by the sensing interfaces (see T4.2) is processed and put into the context of the current situation by the scene understanding module (see T4.3) to enhance the degree of information of the sensed data. The behaviour optimization receives predictions of the surrounding participants in the form of longitudinal velocity/acceleration profiles and assignments to possible path segments. The paths mainly describe the lateral behaviour options of the interaction partners. The longitudinal velocity profiles as well as the path segments will be part of the output of the behaviour understanding and prediction modules developed in T2.3/T3.3 for the internal and external road users, respectively. Participant intentions can either be integrated in these predictions or will lead to an explicit assignment of multiple possible future trajectories within the optimization. Performing the behaviour optimization for multiple future options allows to consider potential intention-based outcomes of the situation (e.g., ego drives first, other second or ego-drives second, other first) and gives the ability to adjust the recommendation accordingly.

5.2 Cooperation Modelling and Optimization

The mode of operation is similar to [2]. The situation understanding detects the cooperative nature of the traffic situation and determines a share traffic space (STS) which is a path-related geometric shape for which the interaction partners compete. Symmetric scenarios with no clear resolution require negotiation of the cooperation partners for the passing order of the STS. Thus, the system plans and optimizes its behaviour for different predictions with different outcomes. The concept of cooperation allows for not only considering the own benefit but also taking the interests of other road users into account.

A behaviour is generated through optimizing a future velocity profile of the ego-vehicle, using the current behaviour of the driver as an initial state. Besides a set of fixed standard velocity profiles (e.g., strong braking, soft braking, constant velocity), two optimized velocity trajectories with different parametrizations are evaluated. During the optimization of these trajectories, the numerical optimizer modifies five velocity support points such that it can search a wide spectrum of longitudinal behaviour. The optimization is performed for all respective path options of the ego-vehicle and of other participants, which are provided by the prediction modules. The optimizer evaluates the trajectories with respect to three main quality criteria: risk, utility and comfort [5]. The utility of a specific trajectory is proportional to the distance covered within the time horizon. The comfort of a trajectory is calculated by applying a weighted quadratic penalization to longitudinal and lateral acceleration as well as longitudinal jerk. Additionally, velocities that exceed an assumed comfort velocity are punished. To assess the risk of a trajectory, the probability of the future location of an object is modelled as a two-dimensional Gaussian function that is centred and oriented along its respective path and evolves with respect to its velocity profile. The probability of a collision between two objects corresponds to the product of their two-dimensional Gaussians (see [6] and [7]). The variances of the Gaussian functions are adjusted to model uncertainties in the future movement of an object. By doing so we can account for uncertainties in the future location due to the uncertainty in the predicted velocity profile. The variances are adjusted both for the longitudinal and the lateral axis of an object which results in ellipsoid shaped two-dimensional Gaussians that grow over time. In case the path of an object takes a turn, the original Gaussian function is divided into several smaller Gaussian components that are oriented along the bended path, thus approximate the original Gaussian by a Gaussian Mixture Model that follows the curvature of the path. For each prediction time step, the actual collision risk is computed by multiplying the collision probability with the severity of a potential collision using a semi-elastic two-dimensional collision model. This risk evaluation is executed with respect to all traffic participants regarding their different path options. Finally, all risks associated with an ego trajectory are summed up use survival analysis (see Eggert et al. 2017), which prevents unrealistic risk chains, and combined into a single value that represents the total risk for this specific trajectory. Survival analysis also makes sure that events which happen in the far future are less likely than events that take place in the near future. After the risk evaluation of all ego trajectories, the selection of the final trajectory takes into account the risk, utility and comfort costs and also considers the impact of the selection on the required behaviour of other participants.

The system generates trajectory-based plans which are sufficient to control an automated driving system as it was done in the original system by Probst et al (2021) and Wenzel et al. (2021). A simplified variation of the system was previously also used to generate explicit behaviour recommendations for a driver for highway situations [5]. The HEIDI system is also designed as an assistant system for manual drivers. However, it should also explicitly address cooperation with other traffic participants. Therefore, some adaptations have to be developed to use the system in this new context. Firstly, the cooperative aspects are integrated in the evaluation of the quality of planned trajectories. Secondly, predictions of the driver behaviour are computed and integrated into the optimization process, also integrating tracking if the behaviour follows previous recommendations. Additionally, uncertainty about the behaviour of the ego-vehicle is higher in the ADAS case (HEIDI) than in the AD case, where the system itself is in control of the ego-vehicle, which is explicitly considered when optimizing trajectories. Finally, explicitly modelling risk for pedestrians requires some changes to the original formulations.

5.3 Usage in cHMI logic

The cooperative HMI build in HEIDI will use the optimal behaviour selected by the system along with the corresponding optimal behaviour of the other traffic participants (e.g., if “ego” should go first, pedestrian should go second) to provide a coordinated recommendation for both. The underlying system makes sure that the plans are feasible and consistent over time. The presented behaviour optimization module will output behaviour recommendations to the HMI logic. In the combined implementation of internal and external HMI, the recommended behaviour will be processed by the cooperative HMI logic together with information from the environmental sensing, the resolution tracking and previous communication. The cooperative HMI logic has the aim that both driver and participants adhere to the recommended behaviour and through that the situation will be resolved in a way that is best for both and prevent unnecessary hesitation.

6. Situation Resolution Tracking

Once the recommended behaviour has been optimized and the corresponding HMI logic has been followed in order to activate the cHMI, the situation has to be tracked with a view to assessing to which extent the interacting partners (driver and pedestrians) are following the recommended joint action indicated by the cHMI. For this task, it is initially envisioned to implement an update rate of 1-2Hz. Assessment of expected behaviour is a complex task that must be undertaken from a probabilistic standpoint. A proposed solution for that purpose is the use of Knowledge Graphs (KG) [8], given their ability to encode the knowledge in a form that is human interpretable and amenable to automated analysis and inference. A Knowledge Graph is a directed heterogeneous multigraph that can represent multiple, asymmetric relations among entities, where these relations have domain specific semantics. KGs have the ability to integrate information coming from sources of different nature. In the context of the targeted problem, the *graph entities* will be the different road users, their associated features/behaviours, and the different contextual factors (pedestrian crossing, traffic conditions, etc.) affecting their behaviour, while the *graph relations* will describe the interactions among the *graph entities*. In a KG, entities and relations are bounded together by means of triplets represented by a *(h,r,t)* tuple, where *h* is the head (or subject) entity, *t* is the tail (or object) entity, and *r* is the relation associating the head with the head entity. A few examples of triplets in the context of road users' behaviour are given next: *(pedestrian-i, Has-Feature, Looking-At-Driver-Vehicle-j), (Vehicle-j, Is-Located-Behind, Vehicle-k)*. In these triplets, the heads, tails, and relations can be clearly identified. Knowledge Graph Embeddings (KGE) [9] are low dimensional representations of entities and relations in a KG. They provide a generalizable context about the overall KG that can be used to infer relations. KGEs define different score functions that measure the distance of two entities relative to its relation type in the embedding space. These score functions are used to train the KGE models so that entities connected by relations are close to each other while entities that are not connected are far away. KGEs are used for completing KGs by predicting missing links and entities by reasoning on existing facts. This ability can be used for assessing the current behaviour of a road user, e.g., (*pedestrian-i, Has-Intention, Cross-Street*) or (*driver-j, Has-Intention, Give-Way*). A probability can be computed for each tuple using KGEs. Thus, KGEs can provide a probabilistic assessment of how likely it is that each interacting partner is following the proposed joint recommendation.

Assessment of each partner's behaviour can be carried out independently using the contextual information so that a global, joint probability can afterwards be computed for the overall interaction. The computed probabilities will then be used in the decision module to assess the degree of success that the current cHMI action is achieving. In case the interacting partners are not appropriately following the optimized recommended behaviour, the decision module can take one of the following possible actions: i) continue with the proposed joint recommendation, under the assumption that the situation can still be solved following this joint action, but eventually increasing the "urgency" of the HMI communication. This will have an impact on the intensity and/or the nature of the HMI message. This means that the cHMI can opt for using more pressing interfaces, such as, e.g., audio and infotainment; ii) compute a new, alternative joint behaviour given the current situation. This implies that the newly selected action will not be the optimal one but it will still be enough to solve the situation in an acceptable manner. In this case, safe and efficient actuation will come at the expense of suboptimality. The continuous resolution tracking module can change the selected decision several times in the course of the interaction until the partners complete such interaction following some of the proposed joint recommendations or until the system comes to a safe fallback behaviour.

7. Conclusion

This deliverable has presented the main concepts of the HEIDI Human-Machine Interface (HMI). These concepts build upon a holistic approach that expands the fluid HMI principles, resulting in a highly connected and flexible system. The HEIDI fluid HMI concept, representing continuous and seamless interactions between vehicle and driver, is extended to include the exteriors of the vehicle and engaging also pedestrians in a cooperative action. Therefore, this approach considers the two sides of the vehicle, i.e., the inside to the outside, as part of a single interaction and communication system.

The use cases and sequence diagrams described in D1.2 informed the development of underlying decision logics for the internal, external and cooperative HMIs, respectively, with the goal to optimize driver-vehicle-pedestrians' interactions in terms of safety, efficiency, and comfort. Different user profiles (state and type) are considered in the iHMI logic. Therefore, the HMI logics describe the abstract algorithms that process sensed data from inside and outside the vehicle to trigger respective HMI actions, i.e., anything that is displayed via HMI (light, icons, sounds, etc.).

The initial version for the decision logics of the internal and external HMI are presented. These logics and the resulting HMI design will be independently investigated in explorative studies in WP2, WP3, and WP5. The outcome of these studies will then be incorporated into a combined cooperative HMI logic, which will serve as integrated implementation of internal and external HMI.

An initial version of the cooperative HMI logic is also presented in this deliverable. The logic of the cooperative HMI depends on the situation and its evolution. Therefore, the behaviour optimization module of the cooperative HMI logic will produce behaviour recommendations based on environmental sensing, the resolution tracking and previous communication. The (planned) combined implementation of internal and external HMI logics will display the recommended behaviour as processed by the cooperative HMI logic here presented.

8. Abbreviations

Term	Definition
D	Deliverable
HEIDI	Holistic and adaptivE Interface Design for human-technology Interactions
HMI	Human-Machine Interface
KG	Knowledge Graphs
KGE	Knowledge Graph Embeddings
PU	Public
R	Document, Report
STS	Share traffic space
TTC	Time To Collision
VRU	Vulnerable Road Users
WP	Work Package

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