Designing cooperative interaction of automated vehicles with other road users in mixed traffic environments

interACT D5.3 Technical verification plans and Outcomes

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Glossary of terms

Term	Description
CTRA	Constant Turn Rate and Acceleration, a model for vehicle trajectory prediction
Docker	A set of platform as a service products that use OS-level virtualization to deliver software in packages (containers)
dSpace	A repository software package, used in the Trajectory Planner module.
DTI	Distance to intersection, metric for vehicle’s spatial proximity to point of interest
IPG Car Maker	Tool for virtual testing of automobiles and light-duty vehicles
ROS (Robot Operating System)	Robotics middleware used in the CCPU, for internal component communication.
rqt	A graphical framework, used for development in ROS.
TTI	Time to intersection, metric for vehicle’s temporal proximity to point of interest

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List of abbreviations and acronyms

Abbreviation	Meaning
AV	Automated Vehicle
CAN	Controller Area Network
CCPU	Cooperation and Communication Platform Unit
CTRA	Constant Turn Rate and Acceleration
DDD	DLR Driver Display
DGPS	Differential GPS
ECU	Electronic Control Unit
eHMI	external HMI
EPS	Electric Power Steering
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSM	Global System for Mobile Communications
GUI	Graphical User Interface
HMI	Human Machine Interface
HMM	Hidden Markov Model(s)
iHMI	internal HMI
LED	Light-emitting diode
LK	Lane Keeping
MPC	Model Predictive Control MPC
NP	Normal Production
NTRIP	Networked Transport of RTCM via Internet Protocol
PP	Perception Platform
PPLAN	Path Planning

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PU	Polyurethane
ROI	Region of Interest
RTCM	Radio Technical Commission for Maritime Services
SA	Situation Awareness
SVC	Stereo Video Camera
SW	Software
TL	Left Turn
TP	Traffic Participant
TPL/TPLM	Trajectory Planning / Trajectory Planning Module

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Executive Summary

A basic challenge that emerges when introducing Automated Vehicles (AVs) into a mixed traffic environment is the extension of the traditional two-way human-to-human cooperation (e.g. driver with road user) into a three-way cooperation (e.g. AV, on-board user, road user). To address this challenge, the interACT project develops solutions that aim to improve the following aspects:

- Communication between the AV, the on-board user and other road users, using appropriate HMI elements.
- Control of the AV's actions in an integrated, well-synchronized manner.
- Safety of AV's interactions, by means of self-verification.

To that end, Task 5.2 focused on the integration of all software and hardware components (previously developed in Work Packages (WPs) 2, 3 and 4) into the demonstrator vehicles, together with the respective sensor fusion and adaptation of control algorithms.

Now, this document describes work done in Task 5.3 (T5.3), about the technical results from the functional tests (according to requirements and specifications mainly of the components) and then from the integration tests of the complete system.

In detail, after the implementation stage, communication tests between the components and on-road functional tests were performed during T5.3, to ensure proper functionality and to guarantee that the system is ready for the evaluation phase. In this perspective, we supported both the Evaluation Plan, together with WP6, to provide a suitable outline of the test plan (e.g. tests are feasible and in project scope) and the User Interaction Evaluation Tests, in order to verify system performances in terms of user-related criteria.

In conclusion, tests on single components and functionality tests on the whole system were OK (all details available in the main text). This means that all sub-systems and modules constituting the interACT system (Perception Platform, CCPU, eHMI, etc.) could be installed and integrated on the prototype-vehicles. Based on that, the two demonstrators (one from CRF and one from BMW) were ready for the evaluation phase (in WP6) and for the final demonstration.

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1. Introduction

This document is structured as follows. After this introduction (Ch. 1), in Chapter 2, we describe the test methodology, including the test-scenarios for the evaluation of the complete interACT system. Chapter 3 describes the verification of the system components, namely the module constituting to the Cooperation and Communication Platform Unit (CCPU), performed on the CRF car. Chapter 4 deals with the main achieved results of the interACT system, fully implemented on the CRF demonstrator, in terms of functionality. Chapter 5 and 6 are related to the BMW demonstrator, with the description of the integration test process and the test results of the interACT system, as implemented on BMW demonstrator, respectively. Chapter 7 represents the conclusions, in which we discuss the outcomes of WP5 and we include also the final remarks and the lessons learnt.

1.1 Purpose and scope

The purpose of this deliverable is to describe the technical results from the functional tests (according to requirements and specifications of both the components and the whole application).

Primarily, the scope of the document, in alignment to Milestone 7 “interACT solutions evaluated and demonstrated”, is focused primarily on the technical verification and execution of preliminary tests to verify modules, components and systems against functional requirements and specifications in WP2 (e.g. the description of how the system should work and how it should react in a given situation). In addition, this document describes how the support for the Evaluation Plan (together with WP6, to ensure that tests are feasible and in project scope) and for the User Interaction Evaluation Tests (together with WP6, to verify the system performances with respect to functional requirements) has been provided.

Finally, here we provide the details about the preparation of vehicles for final demonstration, including external/internal HMI implementation.

1.2 Intended readership

The process of final demonstrations preparation, reported in this document, was a useful tool to summarize the work in WP5. Partners that are involved in WP5, can use the aforementioned material for the finalization of the CRF and BMW vehicles, towards technical evaluation and preparation of the final demonstration (Milestone 7 “interACT solutions evaluated and demonstrated”).

In parallel, it is both a tool and a source of information for WP6 partners, which can use these demonstrators for the WP6 evaluation and behavioural studies that are conducted there. Partners from previous WPs (2, 3, 4) may also monitor the realisation of their developed components into the actual demonstrators and the end-to-end system performance. Finally, the document will serve as demonstration of the final integration process of prototype vehicles in WP5 for our Project Officer, the reviewers and the European Commission.

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1.3 Relationship with other interACT deliverables

As depicted in Figure 1, WP5 utilizes the results of WPs 1, 2, 3 and 4 (developed components, processes and their interconnection). It mainly concerns the setup of the demonstrator vehicles (integration and testing of all components), while its outcome is evaluated in WP6.

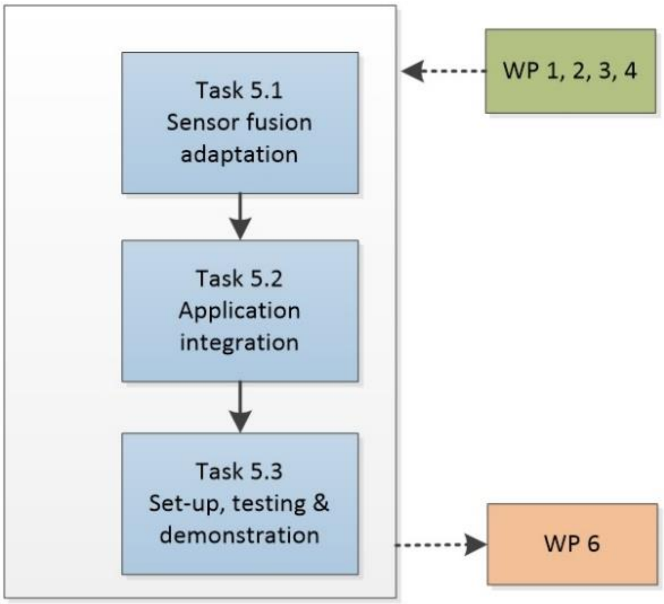

Figure 1: WP5 relation to other WPs

The related deliverables that describe the elements that are incorporated in the vehicles are the following: **D1.2** "Requirements and system architecture and interfaces for software modules", **D2.3** "Sensors and algorithms incorporating the developed models to be integrated into the demonstrator", **D3.2** "Cooperation and Communication Planning Unit prototype and accompanying report", **D4.2** "Final interaction strategies for the interACT AVs", **D4.3** "Interaction design and HMI solutions for driver and other traffic participants" and **D5.2** “Interaction function integration. Demonstrator final version”.

Future deliverables that will be affected, are mainly the ones related to the demonstrators’ evaluation: **D6.2** "Evaluation report on on-board user and road users interaction with AVs equipped with the interACT technologies" and **D6.3** "Impact assessment of external AV HMI on traffic cooperation, traffic flow, infrastructure design and road safety".

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2. Test Plan Description

In this section, we describe the plan we adopted to test the whole interACT system, as implemented on the CRF demonstrator, which is able to perform autonomous driving at low speed.

The following figure shows the high level system architecture, as originally presented in D1.2 and D3.2:

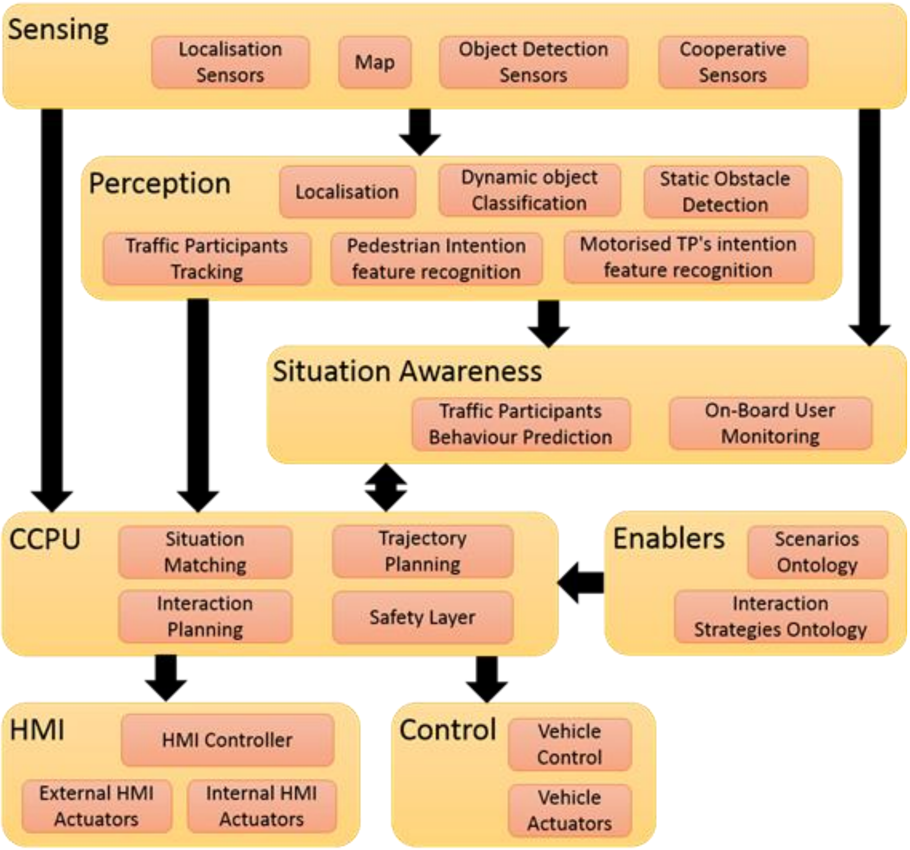

Figure 2: original interACT architecture.

Focusing on the "Cooperation and Communication Platform Unit" (CCPU), it consists of four components, shortly described as following (more details can be found in D3.2). The Situation Matching module is the entry point of the CCPU and its main functionality is to match the real-time traffic situation with the predefined digital scenarios. Furthermore it narrows down the detected TPs around the AV to the ones the AV has to interact with. The Interaction Planning module is then responsible for planning and executing a coherent and consistent sequence of actions in terms of implicit and explicit communication. As a result, it generates instructions for the HMI and for the trajectory planning module, in form of constraints for the related control. The Trajectory Planning module takes these constraints and provides real-time updates of the optimal trajectory along the prediction horizon. In the end, the Safety Layer module verifies the given trajectory in terms of safety, by computing set based occupancies of other traffic participants. Updates to the structure can be found in section 3.6.

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The whole interACT system is fully implemented on the CRF car, so in the following sections we will mainly refer to this demonstrator for the system evaluation.

2.1 Methodology

The methodology of the technical tests for the interACT system is divided in two main parts: one related to the validation of the CCPU components, as implemented on the CRF demonstrator and another one related to evaluation of the complete system. In this section, we describe how the experiments were conducted, as well as the related scenarios and the test-site used. In the next chapters, the results will be presented and described.

2.2 Experiments

We ran different experiments for the validation of the single components and for the evaluation of the whole system.

For all tests, we have performed 5 runs each, to achieve minimum statistical significance.

Tests, including the interaction of the Autonomous Vehicle (AV) with another vehicle, were conducted using a collaborative car.

The maximum speed of the AV was around 15 km/h.

2.2.1 Test-scenarios

This paragraph presents the test-scenarios we considered both for the validation and evaluation, based on the applicative scenarios and related use-cases, as described in WP1 (for more details see the project deliverables D1.1 and D1.2). The graphical representation of the test situation is provided with a complementary scenario description, in order to illustrate how the CCPU works. In particular, we considered two types of scenarios (as aforementioned): the interaction with pedestrian and with another vehicle (manually driven).

For the first case, the situation is sketched in the following figure:

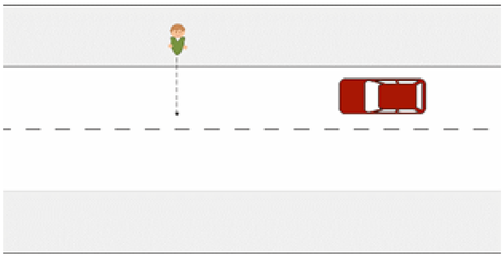

Figure 3: graphical representation of the scenario involving the interaction with VRU (pedestrian), crossing the road ahead the AV.

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In the case depicted in the figure, the AV has to react to a single pedestrian who intends to cross vertically the road at a point with no zebra crossing and on a straight road segment with no traffic lights. The pedestrian appears in front and on the right side of the AV that is driving straight. The crossing distance from pavement to pavement is 3m-10m. The road is a two-directional road and the pedestrian is detected (un-obscured) close to the crossing, on the right side of the AV. In our test-case, we considered that pedestrian is waiting for the vehicle to show action, before crossing the road.

There are two types of interaction with another vehicle (second case), as skectched in the figure:

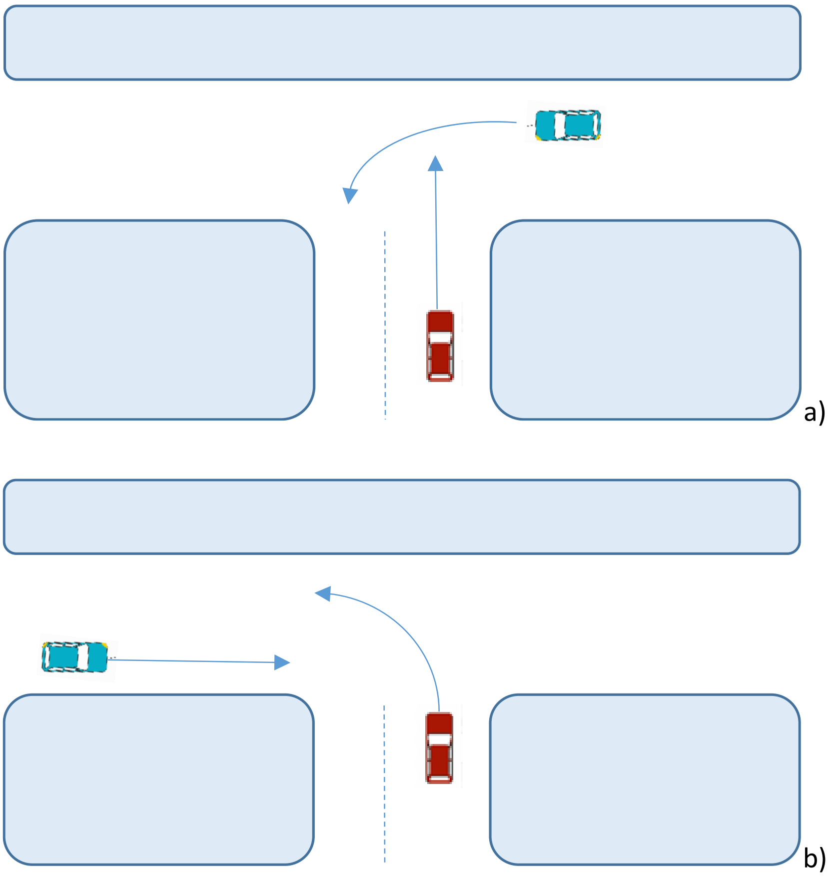

Figure 4: react to other vehicles on the road (emulation of parking zones). The host-vehicle (AV) is in RED, while the obstacle is in CYAN (manually driven).

Here, the AV has to react to another vehicle on the road. In situation a), the AV (in RED) drives straight on towards an intersection, where there is another vehicle (in CYAN), coming from the right (respect the AV), which wants to turn on the left (the RED vehicle has to stop, as the figures shows). In situation b), the AV turns on the left, while the obstacle goes straight on. In both cases, the assumption is that the AV has to stop and give priority to the other vehicle[1]. Both cases a) and b) can represent situations, respectively, where:

1. The AV drives straight on a parking road and another vehicle "cuts-in", intending to turn left and join the parking road on the opposite direction with the AV that continues straight.
2. There is a crossing vehicle from the left side of the AV at a parking T-intersection; the other vehicle drives straight on a parking road, while the AV intends to turn left.

In both cases the AV decides to decelerate and stops, yielding for the other vehicle, based on the other vehicle's intention to cross/cut-in.

2.2.2 Test-site

Due to safety reasons, it was not possible to conduct experiments in real-roads, therefore all tests have been carried out in dedicated areas: the private test-track of Fiat Safety Centre (FSC) for the validation and the evaluation, as well as the private parking area of CRF for a more detailed validation of the Trajectory Planning (TPL) module of the CCPU, which can show the integration and the performances of low-level Control Functions.

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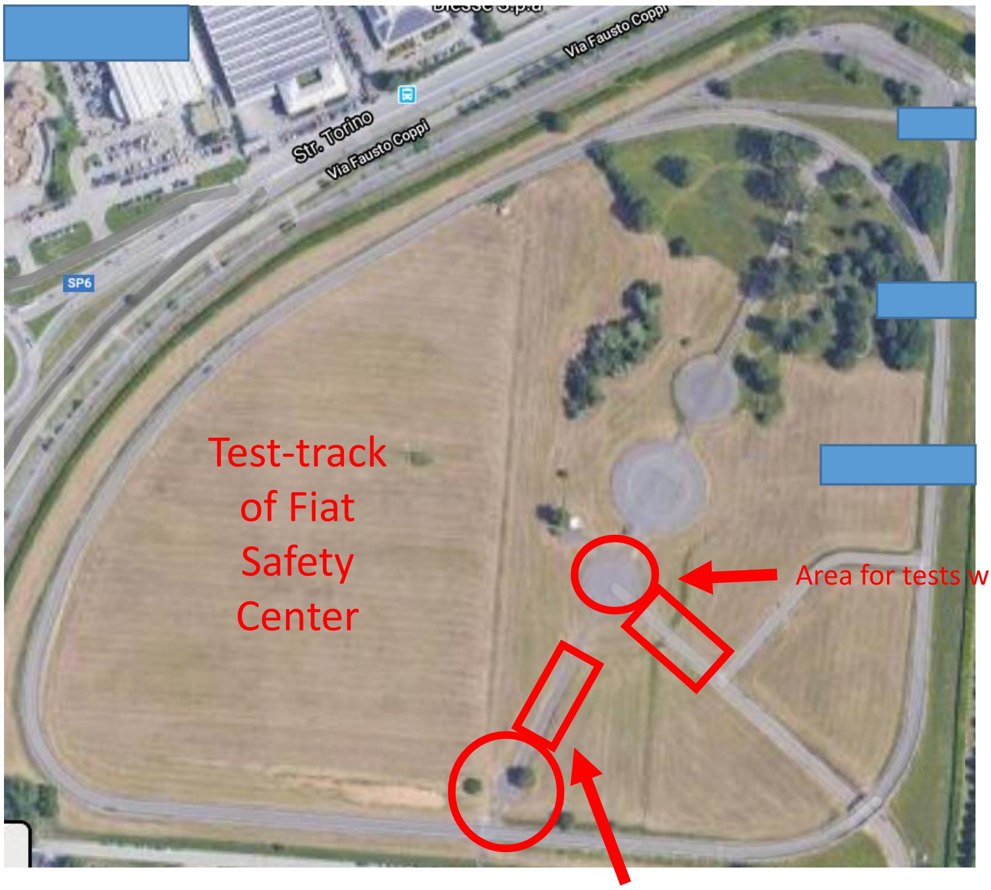
[1] We decided to focus on these scenarios because, as pointed out in D1.1, 53% of all intersection accidents and 59% of the fatalities and serious injuries take place at intersections, where one vehicle drives straight as another vehicle turns left/right (Simon et al, 2009).



Area for tests with other vehicles

Area for tests with pedestrians

Figure 5: private test-track of CRF (in Fiat Safety Centre), with details about how it was used.

Area for tests of Trajectory Planning module, including low-level motion control

Figure 6: parking area of CRF facility, with details for the specific zone used in the experiment.

These two figures sketch the two mentioned areas, one internal to CRF (parking area) and the other one located in FSC (the test-track).

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3. Verification of System Components on CRF Demonstrator

In this section, a verification of the interACT system is provided, through the validation of the main components of the CCPU, as integrated in the CRF vehicle. In particular:

- Traffic Participants' (TPs') intention recognition and behaviour prediction, from ICCS partner.
- Situation Matching (SM), from DLR partner.
- Trajectory Planning (TPL), from CRF partner.
- Communication and Cooperation Platform Unit (CCPU), from ICCS partner.

More details on the implementation of each module can be found in the deliverables of WP3 (e.g. D3.2).

3.1 Validation of Motorized TPs' intention recognition and behaviour prediction

As presented in D2.3 [1], the Perception Platform includes two modules namely the Vehicle Intention Recognition – based on Hidden Markov Model (HMM) – and the Vehicle Trajectory Prediction that are responsible for predicting other vehicles' intentions and future motion. The overall architecture of interACT's motorized TP's recognition and behaviour prediction mechanism is shown in Figure 7.

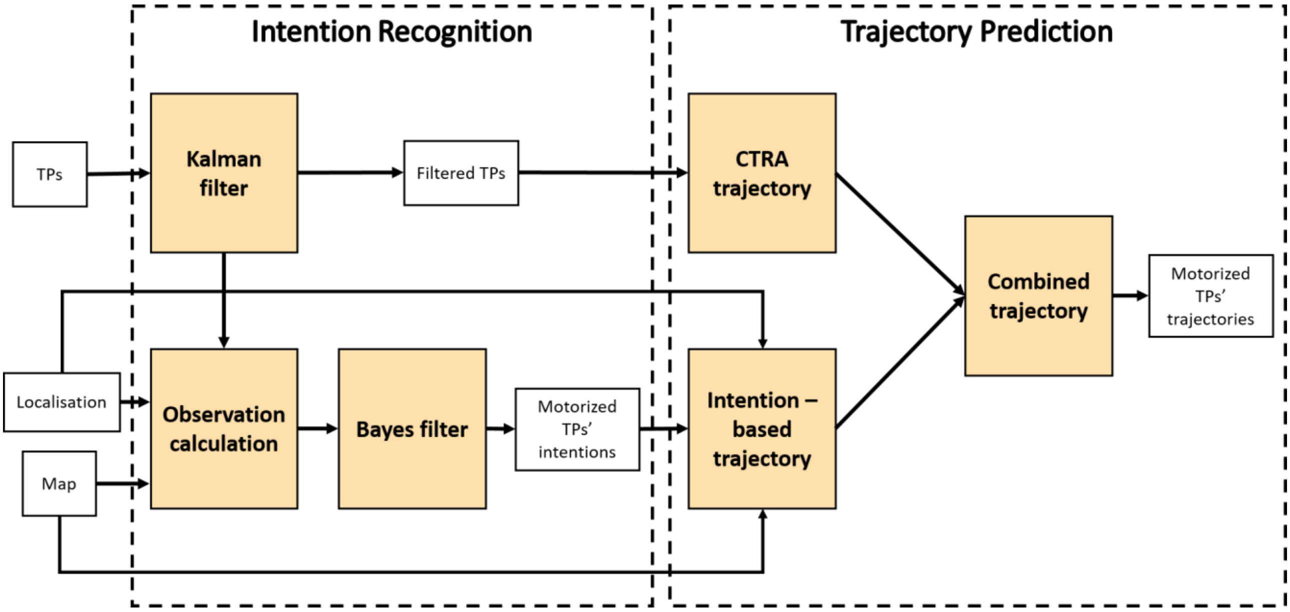

Figure 7: interACT's motorized TP's intention recognition and behaviour prediction architecture.

Validation of the functionality of the modules was conducted as part of the overall algorithm evaluation process, the results of which are subject to submission in the 3rd IEEE Connected and Automated

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Vehicles Symposium (IEEE CAVS 2020). This process consisted of a series of experiments, where the motion of the AV was simulated and the algorithms were applied on the AV itself. Thus, the AV's actual (simulated) route and trajectories were compared against the predicted ones. In the following sections, preliminary results of the evaluation procedure are presented. More details for the pedestrian intention prediction module will be provided in Section 3.2.

3.1.1 Experimental Evaluation via Simulation

The simulation assumes that the AV is moving towards a 4-leg intersection on Abstaat premises (**Figure 8**). On approach, deceleration is applied depending on the speed-acceleration profile (initial data points may belong anywhere upon the stopline L0 of (**Figure 8**) and then the vehicle continues its route towards the target point, which is either located on the next straight lanelet, thus denoting a lane keep (LK) decision, or on the next left/right lanelet, thus denoting a left/right turn (TL/TR) respectively (see L2, L3, L4 in **Figure 8**Fehler! Verweisquelle konnte nicht gefunden werden.).

The simulation is repeated using 4 speed (m/sec)-acceleration (m/sec2) profiles [(5, 0.58), (5,0.72), (5,0), (6,0)], 11 stop-line points and 33 target points (11 per case TL, LK, TR), effectively giving 1452 datasets. The state of the AV along with the outcome of the algorithms are recorded using the ROS framework [2] at a rate of 10Hz, which is identical to the module's operation in the interACT system.

For the evaluation, the trajectory and kinematics data falling inside the evaluation time-window shown in **Figure 8** are considered (from L1 to L0). The algorithm runs from the beginning (Point A) to allow the algorithm to properly initialize the vehicle's state and emission probabilities. For the evaluation of the Trajectory Prediction module more data-points ahead are used as reference from the map together with the above-mentioned simulated datasets. Only the true-positive (predicted intention=actual intention) cases were considered for trajectory determination and comparison.

As prediction horizon is one of the most important requirements of this work, we report the average and maximum time to intersection (TTIs) of the correct turn detection in the TL and TR experiments. Average TTI values are 2.67 sec (DTI=11.02 m) and 2.07 sec (DTI=8.86 m), while maximum TTI values are 4.41 and 3.55 sec for the TL, TR cases respectively. Based on the fact that the above-mention values refer to the CommonRoad map representation [3] [4] (see **Figure 8**, where the distance between L0 and L1 lines is around 6 meters while max velocity is 6m/s), it is estimated that the algorithm can provide a verdict 1 sec earlier than calculated by our method, i.e. at around 3,07 and 3.67 secs for the TL, TR cases respectively before the intersection is actually crossed.

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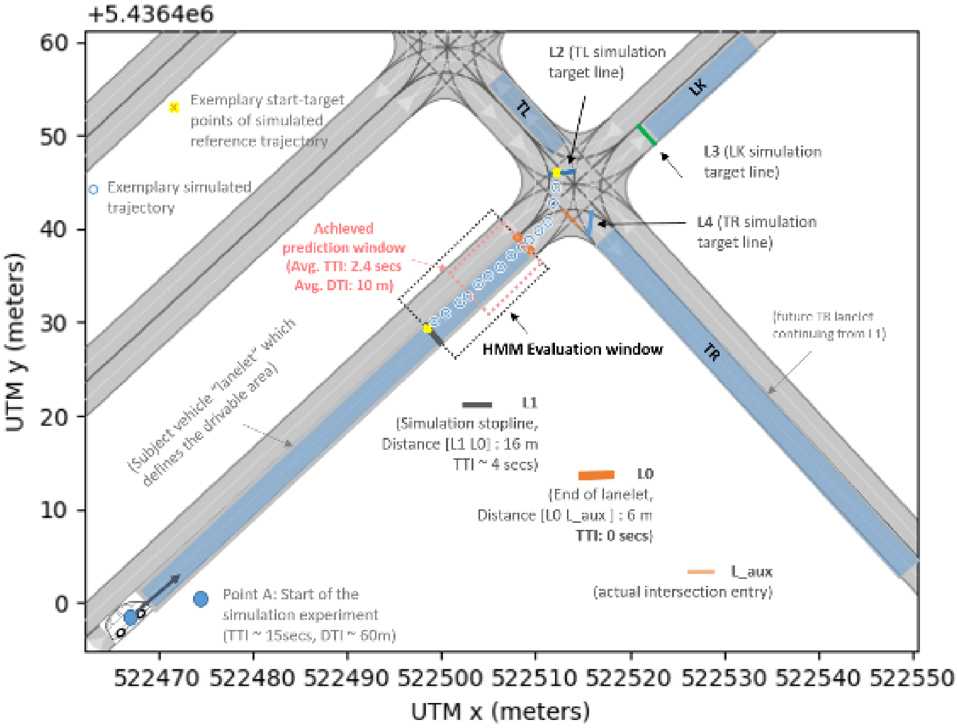

Figure 8: Map representation and points of interests for main setup 4-leg intersection. Vehicle is heading (from Point A) towards the intersection (L_aux) and decides whether to move forward (L3), turn left (L2) or turn right (L4). According to its speed profile, deceleration is applied from L1 and the evaluation outcome is produced between L1 kai L0. Time to intersection (TTI) and distance to intersection (DTI) values are calculated using the CommonRoad map representation tool [4].

For a quantitative evaluation of the prediction verdict consistency we record the percentage of all cases where a turning detection occurs (turning intention probability>s intention probability, for all s) and the algorithm's outcome from that point on remains valid until the end of the intersection. For both the TR and TL cases, this was true in 98.3% and 99.1% of the TR and TL cases respectively. Finally, evaluating end-to-end performance of the algorithm, we obtain 92.2% successful performance, with 4.8% accounting for map errors and 3% of algorithmic failure.

3.1.2 Intention Recognition Results

The outcomes of the algorithm are presented in Fehler! Verweisquelle konnte nicht gefunden werden., in the form of a confusion matrix. The algorithm can provide correct predictions with overall accuracy of 86.7%.

To evaluate the decision outcome of the algorithm the following process was assumed. For each case (TL, LK, TR) the points that reside in the respective average TTI window (see previous section and Figure 7 - evaluation window) are considered, namely 2.67 sec for TL, 2.07 sec for TR, max (TL, TR) for LK. For each data point, the instantaneous intention with the highest probability is compared against the ground truth intention of each case.

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Classifier Result	**TRUTH DATA**			**Classification Overall**	**Precision**
	Turn Left (TL)	Lane Keep (LK)	Turn Right (TR)		
Turn Left (TL)	**1330**	43	0	1373	0.97
Lane Keep (LK)	94	**2513**	42	2649	0.95
Turn Right (TR)	1	22	**603**	626	0.96
Truth Overall	1425	2578	645	**4648**	
Recall	0.93	0.97	0.93		
Accuracy Overall = 95.7%				Kappa = 0.92	

Table 1: Confusion Matrix of Intention Recognition classes

The algorithm can provide correct predictions with overall accuracy of 95.7%. Meanwhile, it is relative fair (precision) across the different classes (TL, LK, TR). The recall values (sensitivity) of all classes is relatively high (0.93 for TL, TR and 0.97 for LK). Lastly, Kappa value is 0.92, a measure of system's performance by comparison to a random selection algorithm (which would essentially give a 33.3% chance for all classes in our case).

3.1.3 Long-term Trajectory Prediction Results

The datasets mentioned above were also used to perform the evaluation of the Trajectory Prediction module. To determine the correctness of the final predicted trajectory two procedures were followed.

A qualitative one, where the final (combined) trajectory was plotted against the respective motion model Constant Turn Rate and Acceleration (CTRA) trajectory (see also **Figure 7**) and against the respective Intention (map)–based trajectory, for each of the three cases (TL, LK, TR). Indicative results are depicted in **Figure 9**, **Figure 10** and **Figure 11**. As expected, the final (combined) trajectory provides a more natural behaviour, guided by the provided map lanelets.

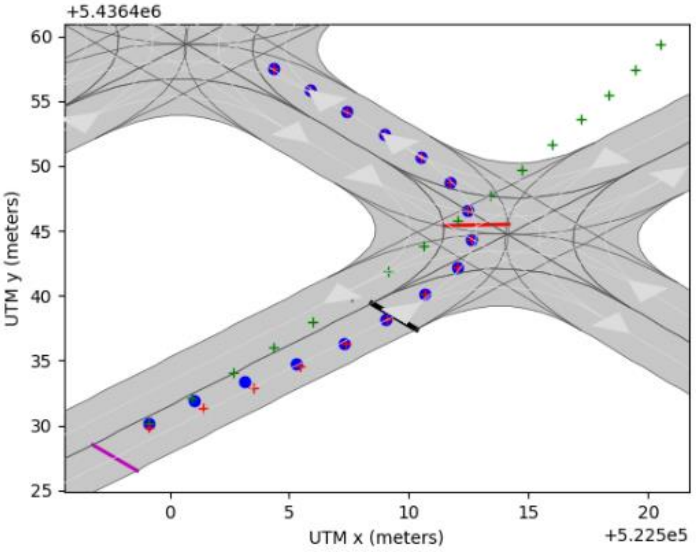

Figure 9: Trajectory prediction (blue dots) versus CTRA (green) versus map-based (red) for the TL case. Magenta line denotes the stopline, black line is the end of intersection and red line is the target line.

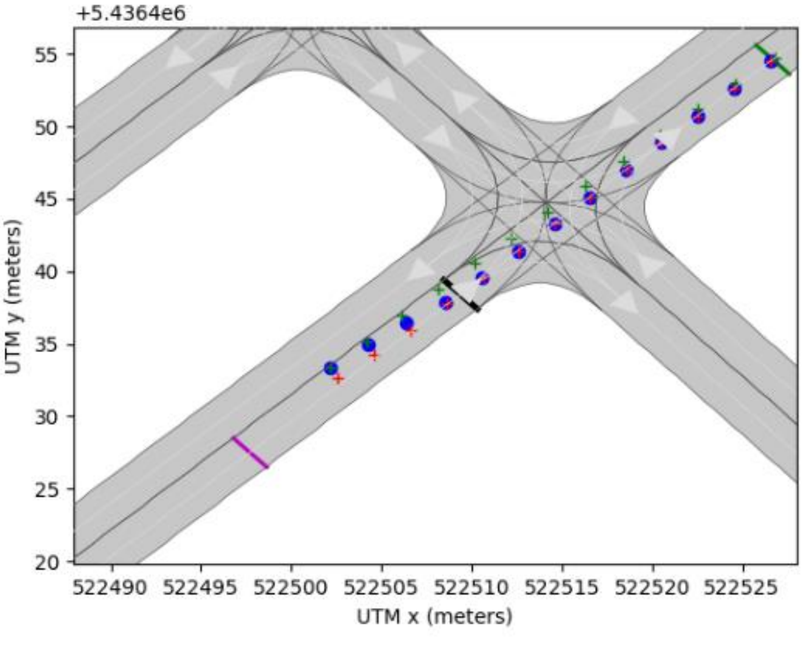

Figure 10: Trajectory prediction (blue dots) versus CTRA (green) versus map-based (red) for the LK case. Target line is denoted with green colour.

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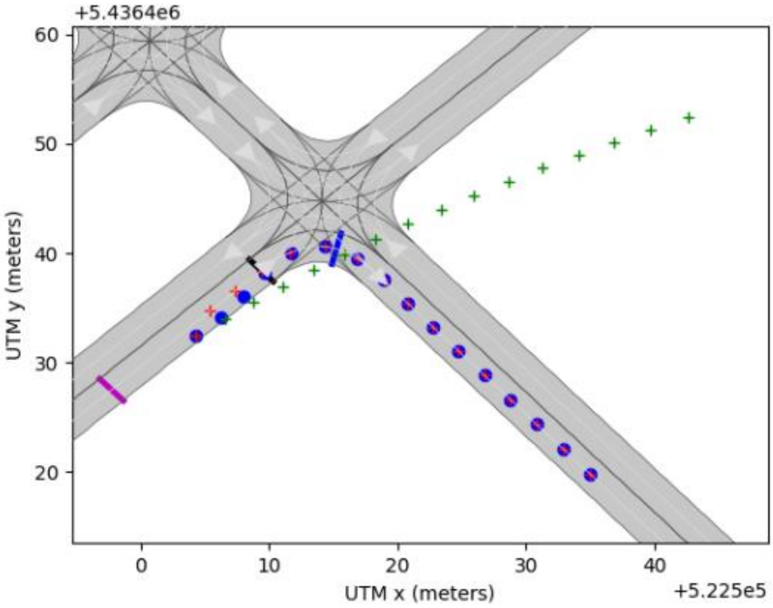

Figure 11: Trajectory prediction (blue dots) versus CTRA (green) versus map-based (red) for the TR case. Target line is denoted with blue colour.

The second procedure included a quantitative analysis method to validate the qualitative results. The differences in distances between the map-based (reference) and the CTRA/Combined trajectories were calculated, using the RMSE metric, defined as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} \{ (x_i - X_i)^2 + (y_i - Y_i)^2 \}}{n}},$$

Where (x_i, y_i) and (X_i, Y_i) are the coordinates of the trajectory under test and the reference trajectory respectively and n the total number of points.

The results are presented in **Table 2**: Trajectory RMSE comparison and match the qualitative results. The combined trajectory tends to reach the Intention-based trajectory, while the Euclidean distance between the combined and the CTRA trajectory is increased, especially in the interval after the initial points.

	TL	***LK***	***TR***
Short-range CTRA (3 points)	1.10	0.54	1.01
Short-range Combined (3 points)	0.51	0.32	0.53
Long-range CTRA (8 points)	1.86	1.18	2.54
Long-range Combined (8 points)	0.38	0.39	0.38

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Table 2: Trajectory RMSE comparison.

Next section presents the validation of the complete CCPU, as integrated on CRF vehicle.

3.2 Validation of Pedestrian Behaviour Prediction

We use the controlled Markov Chains (MC) [17] for predicting the pedestrian's motion. Our approach integrates environmental cues into a physical motion model and yields probabilistic spatiotemporal results. The environmental cues come from both the semantic map and the presence of other traffic participants such as oncoming vehicles. For instance, it can be observed in Figure 12 that a pedestrian is walking on the sidewalk from right to left; the prediction results in 4 seconds indicate that this pedestrian most probably will cross the road using the crosswalk.

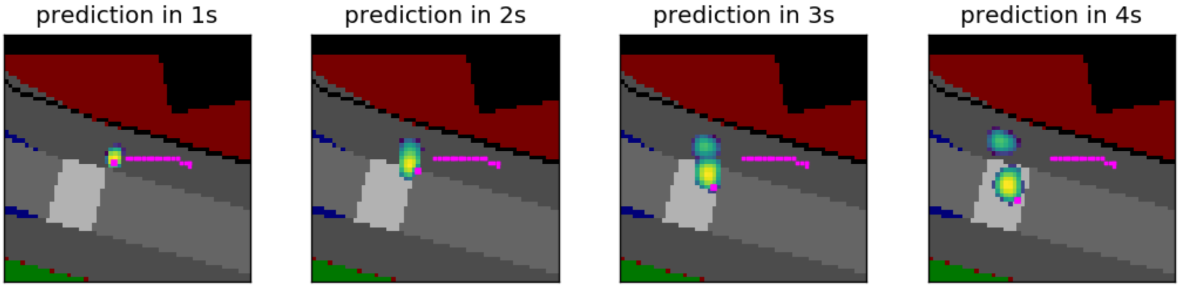

Figure 12: Predicted positions of a pedestrian in an urban environment with the crosswalk (the colours of predicted positions vary from yellow for high probabilities to teal for low probabilities). The predicted pedestrian came from right to left; the dotted magenta lines represent the observed trajectory of this pedestrian until the prediction beginning, while the single magenta point in each subfigure stands for the ground truth position in the future. The underlying semantic map consists of “sidewalk” (dark grey), “road” (grey), “crosswalk” (light grey), “free” (red), “building” (green), “restricted” (dark blue), and “undefined” (black) classes.

3.2.1 Evaluation

Dataset

We evaluate our approach using 300 recordings of real pedestrians in urban environment with and without crosswalks. These recordings were gained from a testing vehicle moving around in the city of Rutesheim, Germany. While the position information of pedestrians is extracted from sensor data, the semantic map is created manually.

Evaluation Metrics

On each recording, we shift the prediction to begin by 0.5 seconds incrementally, so that several different initial conditions for 4 seconds prediction are obtained. The prediction results at points in time (1, 2, 3, and 4 seconds) are evaluated based on the following two metrics:

- Mean absolute error in meter (MAE)

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Let the mean absolute error [2] between the ground truth 2D position $z_t^\eta \in \mathbb{R}^2$ of the ηth trajectory and the predicted positions $x_t \in \mathbb{R}^2$ weighted by their probabilities $P(x_t \in X_i)$ falling into sets $X_i \in \mathbb{R}^2$ be

$$MAE(\eta, t) = \sum_{i=1}^{d} \left\| z_t^\eta - \mathrm{center}(X_i) \right\|_2 P(x_t \in X_i),$$

Where d is the number of sets in the position space and the operator $center(\cdot)$ returns the volumetric center of a set. Then, the mean absolute error over all N trajectories is

$$MAE(t) = \frac{1}{N} \sum_{\eta=1}^{N} MAE(\eta, t).$$

- Precision-recall curve (PR-curve)

We are interested in the probability $p_t^{\eta,ROI}$ that pedestrians will be within a defined region of interest (ROI) consisting of the corridor of the EGO-vehicle and the crosswalk, cf. Figure 13. (It should be mentioned that such a defined ROI is not used during prediction):

$$p_t^{\eta,ROI} = \sum_{i=1}^{d} \mathbf{1}_{X_i \in ROI} P(x_t \in X_i)$$

with the indicator function $\mathbf{1}_{(\cdot)}$ returning 1 if the condition is true, and 0 otherwise.

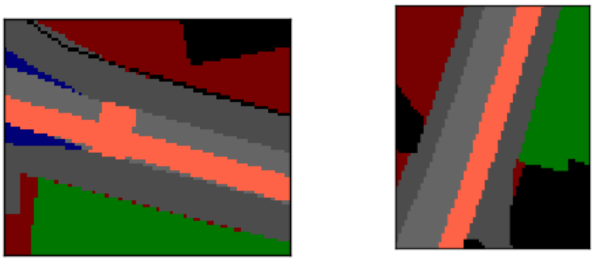

Figure 13: Defined ROI in colour orange in two semantic maps.

To evaluate such a binary classification problem, the precision-recall (PR) curve is often recommended, especially when dealing with skewed datasets. Given the ground truth label $z_t^{\eta,ROI} \in \{1,0\}$ and a threshold $\rho \in [0,1]$, each predicted probability $p_t^{\eta,ROI}$ at the point in time t can be regarded as one of four categories in the confusion matrix: true positive (TP), true negative (TN), false positives (FP), and false negatives (FN). Then, one can compute the precision and recall as

$$Precision = \frac{TP}{TP+FP}, \; Recall = \frac{TP}{TP+FN}.$$

Using different thresholds for the whole prediction results yields multiple points in PR-space, and each point shows the trade-off between the precision and recall. The goal is to be in the upper-right corner of PR-space. [2]

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Evaluation Results

For comparison, an extended Kalman filter (EKF) with a linear model is implemented. The left part of Figure 14 compares the average position displacement error $MAE(t)$, where our approach is better than EKF for a prediction horizon more than 2.5 Seconds. As depicted in the middle and the right part of Figure 14, the PR-curves of our approach is closer to the upper-right corner compared to that of EKF.

While the evaluation in Figure 14 is made based on all recordings, we separately evaluate our approach regarding those scenarios with and without crosswalks. For the scenarios without crosswalks, cf. Figure 15, the performance of both controlled MC and EKF decreases compared to that for the scenarios with crosswalk, cf. Figure 16; however, our approach still performs better than EKF in such interaction-heavy scenarios.

Prediction Examples

Figure 17 illustrates a scenario without crosswalks. The predicted pedestrian is walking on the sidewalk (from bottom to top in the figure), while a vehicle is approaching on the road (also from bottom part and towards the top part of the figure). Due to the possible interaction between these two traffic participants, our approach predicts that most probably this pedestrian will stop at the curb at first and then cross behind the passing vehicle, and also he will probably continue walking on the sidewalk.

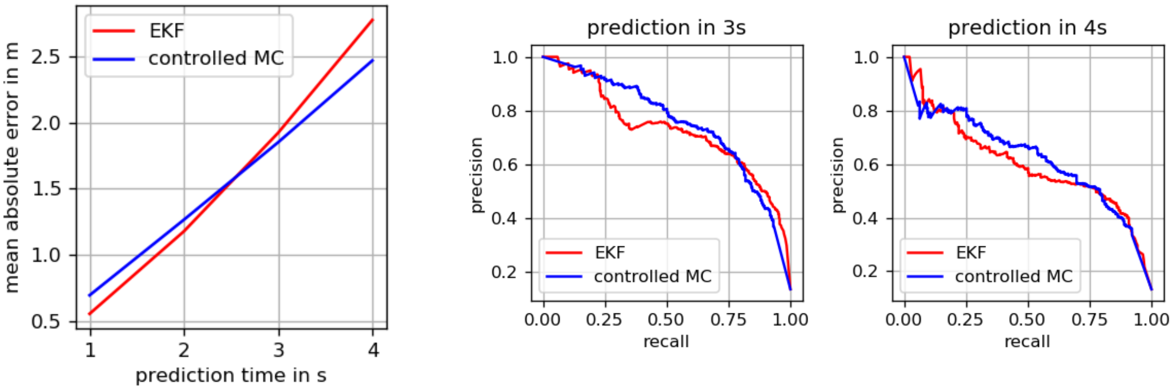

Figure 14: Evaluation using all recordings. The left part depicts the mean absolute error. The PR-curves for prediction in 3 and 4 seconds are depicted in the middle and right part, respectively.

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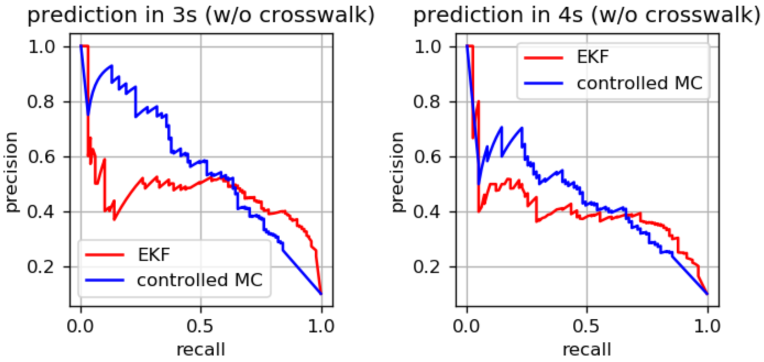

Figure 15: Evaluation on scenarios without crosswalks.

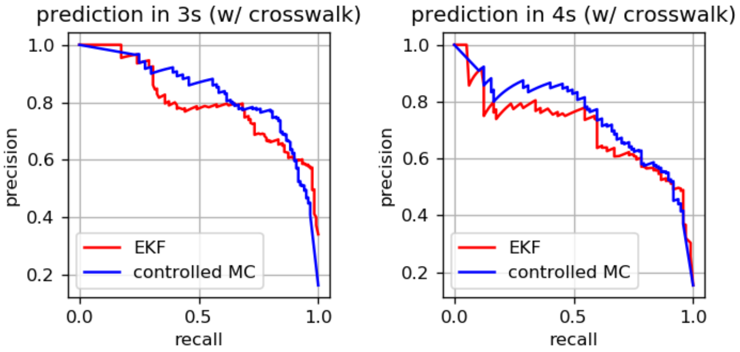

Figure 16: Evaluation on scenarios with crosswalks.

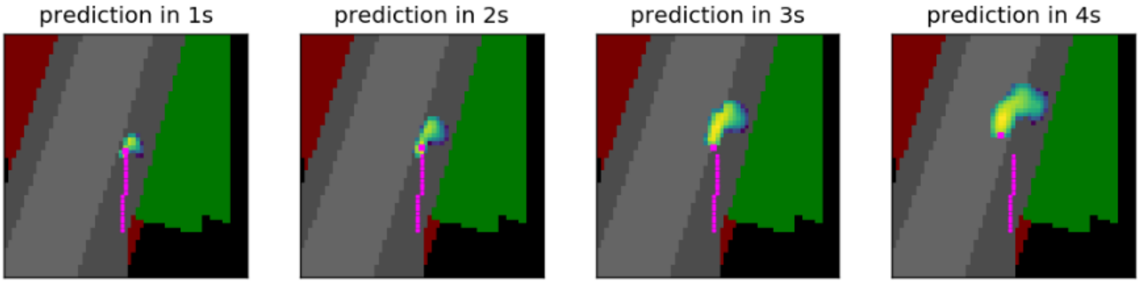

Figure 17: Prediction in an urban environment without crosswalks.

3.2.2 Conclusion regarding pedestrian intention recognition

Our approach yields much detailed spatiotemporal information about where the pedestrian will be and when, as well as the corresponding probabilities. Intentions, such as crossing in front of a vehicle, can be recognized from the predicted probabilistic occupancy, which is typically multimodal distributed. The conducted evaluation shows benefits of our approach for a prediction horizon more than 2.5 seconds.

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3.3 Validation of Situation Matching

Once an AV-to-traffic conflict is detected all CCPU processes are initiated in order to identify the situation and to support the chosen interaction strategy. For all other cases, where no conflict is detected, only the trajectory-related components (CCPU Trajectory Planning and Safety Layer) remain active. Hence, Situation Matching module's traffic conflict detection is decisive for CCPU performance as a whole.

The evaluation performed in simulation covered the four main interACT use cases [5]. As a proof of concept, we are going to report in this section the vehicle-to-vehicle scenarios testing process for **traffic conflict detection and identification**, as this has been defined in D3.2 Sec. 3.3.2.

The initial 35 ROS datasets (rosbags), corresponding to two different T-intersection scenarios and recorded with the interACT prototype vehicle equipped with CCPU in a real-world controlled test environment (CRF test track) [2], were replayed multiple times inserting various artificial delays, resulting in 150 scenarios' variations. The initial datasets included two basic scenarios (see **Figure 18a** and **Figure 18b**) of a conflict between the AV (blue car) and another vehicle (red car), with multiple motion parameter variations (speed, acceleration, initial position). Note that their future paths (denoted with blue and red areas respectively) are 2D trajectories and not mere points, which accounts for the vehicle widths. Also note that the AV's future path is known a-priori, from the information obtained by the Trajectory Planner module.

In scenario (a) portrayed in **Figure 18(a)**, the AV intends to turn left, while another vehicle from the opposite direction is heading straight towards the junction. The motion parameters of the two vehicles are fixed in order to simulate a traffic incident that is supposed to trigger the Situation Matching inference engine, essentially a spatio-temporal conflict, as defined in D3.2 Sec. 3.3.2. As the scenario evolves, the red vehicle eventually stops at the stopline (black dashed line) and gives way to the AV to complete its turn. In a similar manner, in scenario (b) the AV (blue vehicle) is heading straight towards the junction, while the red vehicle intends to turn left. This time the AV stops at the stopline, giving way to the other vehicle to turn.

Tests were conducted to evaluate successful detection of the conflict, as well as other experimental indicators (EIs), shown in Fehler! Verweisquelle konnte nicht gefunden werden..

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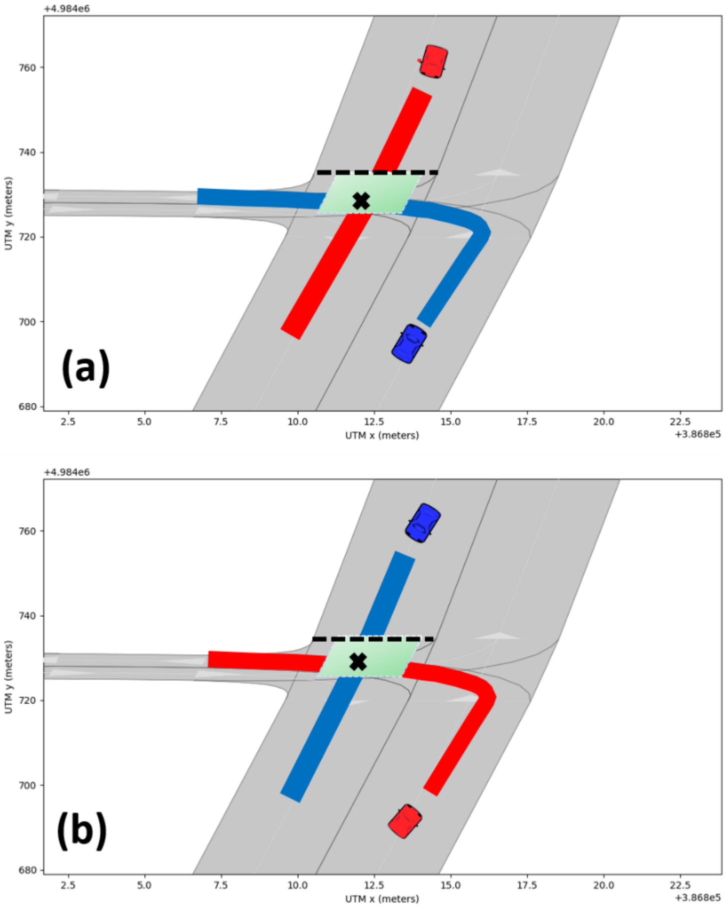

Figure 18: Map representation of vehicle scenarios conducted in CRF premises. AV (blue vehicle) is interacting with a manually-driven (red) vehicle. The blue and red future paths represent their respective 2D trajectories. Spatio-temporal conflict areas are shown as a green gradient square and centre point of the junction with an “x”. Black dashes lines represent the stoplines. Conflict scenarios between (a) turning AV and opposite vehicle, (b) turning vehicle and AV.

In 88% of cases, there was successful conflict detection. The rest 12% account for sensor failure or any kind of system miscalculation due to timing issues (see also **Sec. 3.6.4**). Calibration of hardcoded system parameters and the map is expected to provide better results, however the refinement process was part of the Final Event pre-tests, which were cancelled, due to COVID-19. The following analysis on the EIs is based only on the successful cases.

Firstly, we measured the distance and estimated time to reach the intersection, when the first conflict detection (earliest detection) occurred, as shown below:

$$Distance\ to\ intersection\ (dti) = |Pos_{AV}(x,y,t) - Pos_{INTERSECTION}|,$$
$$for\ t = t\_detection$$

Where:

- *t_detection stands for time when earliest detection occurred,*

- *| | is the 2D eucliedean distance,*
- *Pos_{AV} is the current AV position,*
- *$Pos_{INTERSECTION}$ is the centre of the junction (shown with an "x" in* **Figure 18***).*

The Time to Intersection (*tti*) was calculated from the *dti* and the vehicle's current speed, acceleration. Average *dti* was 11.9 meters and the respective average *tti* was 6.63 seconds. This provides a rough estimate of the distance/time windows from the earliest achieved detection until a potential crash.

Experimental Indicators (EI)	Mean value	Standard deviation
Distance to intersection (dti)	11.9 meters	8.1 meters
Distance from other vehicle	20.8 meters	7.2 meters
Time to intersection (tti)	6.63 seconds	5.1 seconds
Time to other vehicle's current position	10.5 seconds	5.89 seconds

Table 3: Experimental Indicators – Evaluation of Situation Matching

Another indicator measured was the distance (and respective time) between the two vehicles' positions at the time of first detection, which was 20.8 meters (and 10.5 seconds respectively) on average. This provides an estimate of distance and time windows, between the two vehicles in case the other vehicle breaks. Overall it was observed that our software parameter thresholds [5] provided results that far surpassed the confidence levels initially required (i.e. detection before time to collision=2sec). [3]

3.4 Validation of Interaction Planning

The Interaction Planning module plans the behavior of the vehicle and how it communicates its intentions to the other traffic participants. It utilizes both implicit and explicit measures of communication to interact. The implicit measure consists of a speed profile, e.g. an early deceleration indicates that the AV intends to give way. The explicit measures consist of an internal HMI that informs the passengers of the AV about the current situation and an external HMI that communicates the intention of the AV with outside traffic participants.

The Interaction Planning module takes several inputs to calculate its plan. The Situation Matching module delivers the relevant actor identifiers as well as a general environment classification. Combined with the sensor data, the current positions, headings and speed of these actors are available to the Interaction Planning module. This covers the current state of the environment. Additional, the state of the AV is important as it determines relative positions to other traffic participants, the absolute position of the AV on the map and thus along the planned route of the AV as well as the current speed of the AV.

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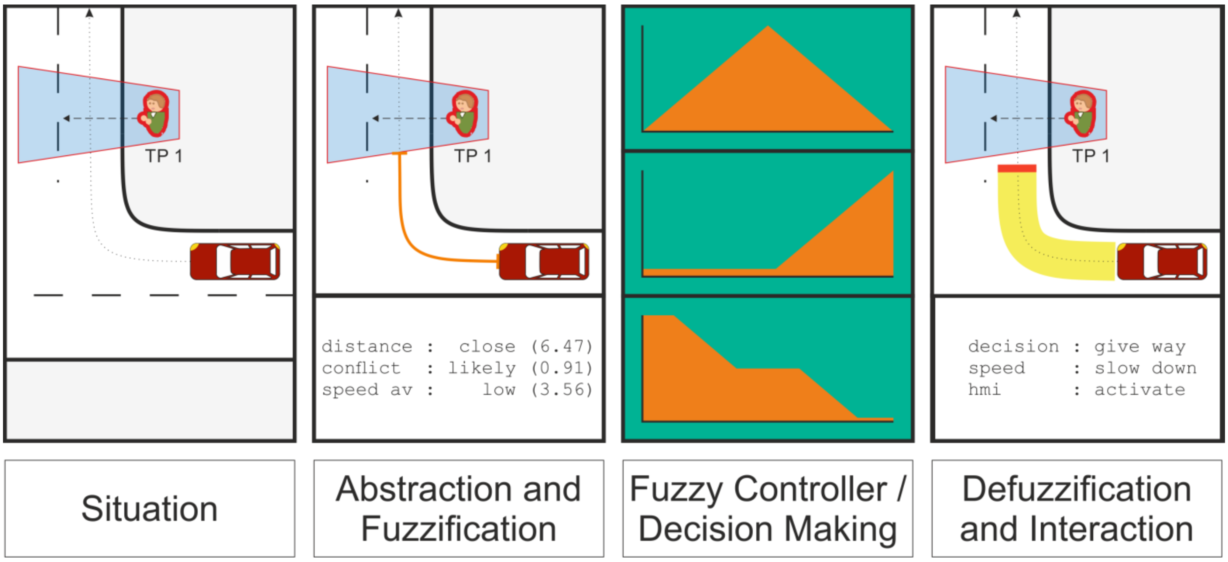
This information is enriched by the data from the Vehicle Intention module and the Pedestrian Intention module. Both provide estimations of the future behavior of the other traffic participants. The Vehicle Intention module provides likely paths for motorized traffic participants, while the Pedestrian Intention module provides a heat map with the most likely locations of non-motorized traffic participants over the next few seconds. Both enable the calculation of possible conflicts with the planned path of the AV.

For the decision making unit that is responsible for the actual planning within the Interaction Planning unit, the following values are extracted from the inputs:

- the environment classification from the Situation Matching module,
- the type of the conflict partner from sensor data,
- the estimated distance to the conflict from the intention modules,
- the likelihood of the conflict from the intention modules and
- the current speed of the AV from the sensor data.

These values are fed into the decision making unit implemented as a fuzzy controller. Fuzzy controllers use membership functions as one of their inputs, e.g. a traffic participant can be anywhere between ‘close’ and ‘far’ from the vehicle, represented by a fuzzification of the estimated distance to the conflict. Similarly, the AV can be ‘slow’ or ‘fast’. The values are fuzzy because a clear assignment is not possible. With the given rules, the controller then generates a fuzzy output that is translated back into a crisp value via de-fuzzification. The different steps are shown in the following Figure.



```
distance  :  close  (6.47)
conflict  :  likely (0.91)
speed av  :    low  (3.56)
```

```
decision  : give way
speed     : slow down
hmi       : activate
```

Figure 19: The detected situation is abstracted, fuzzified and evaluated by a fuzzy controller. The result is a decision on how to handle the situation

The result is a general decision of whether the AV will give way or not and potentially, depending on the decision, a speed profile and a stop line. A speed profile consists of one or more positions, i.e. lanelet identifiers and progresses along the lanelet, on the map and a given maximum speed value. When the AV reaches such a speed limit, it is not allowed to exceed that speed limit until another one is reached.

Similarly, a stop line also has a position that may not be passed until the stop line is removed by the Interaction Planning module. These constraints are directly forwarded to the Trajectory Planning module via their respective topics in ROS, thus influencing the behavior or implicit communication of the AV. Additionally, the HMI is controlled as described next. The overall inputs and outputs of the Interaction Planning module are shown in the following Figure.

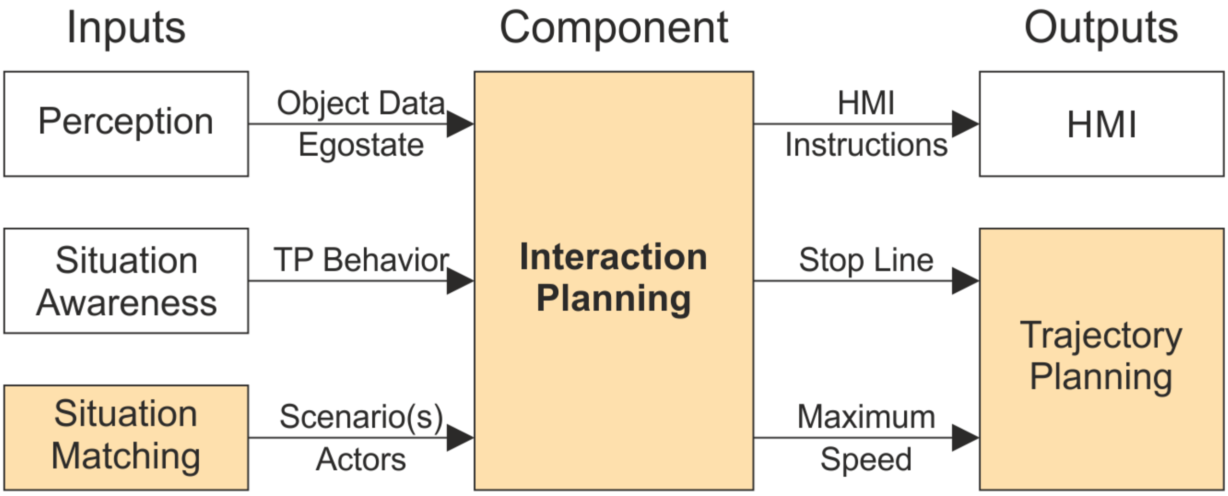


Figure 20: In- and outputs of Interaction Planning module with components of CCPU colored orange.

The HMI consists of two parts, an internal HMI to communicate the current situation to the passengers of the AV and an external HMI to communicate the situation to the (external) traffic participants. It is continuously controlled as the situation develops. For the internal HMI, a display was implemented and as depicted on the left in Figure 15. The display is connected via ROS directly to the Interaction Planning module and gives an overview over the current situation and the intention of the AV.

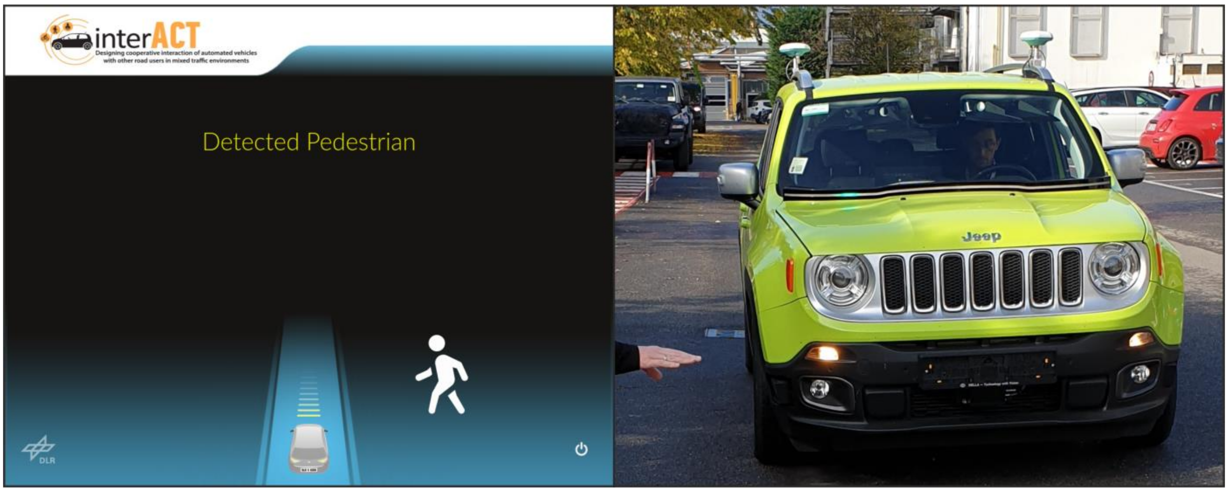


Figure 21: Internal HMI (left) and external HMI (right, perception based).

The external HMI, also shown in Figure 21, has its own controller that controls the hardware integrated by HELLA. It is controlled via the CAN bus of the vehicle. Thus, an eHMI interpreter component was necessary that translates the ROS messages of the Interaction Planning module into CAN messages to give the proper commands to the eHMI hardware controller. The resulting overall structure for HMI control is shown in Figure 22. This structure also allows the CCPU to be completely separated from the concrete implementation of the iHMI and the eHMI, enabling easy extension and further developments both in the CCPU and the HMI hardware. The direction of the light is adjusted at 10 Hz to ensure optimal addressability and follow the traffic participant for the whole duration of the interaction.

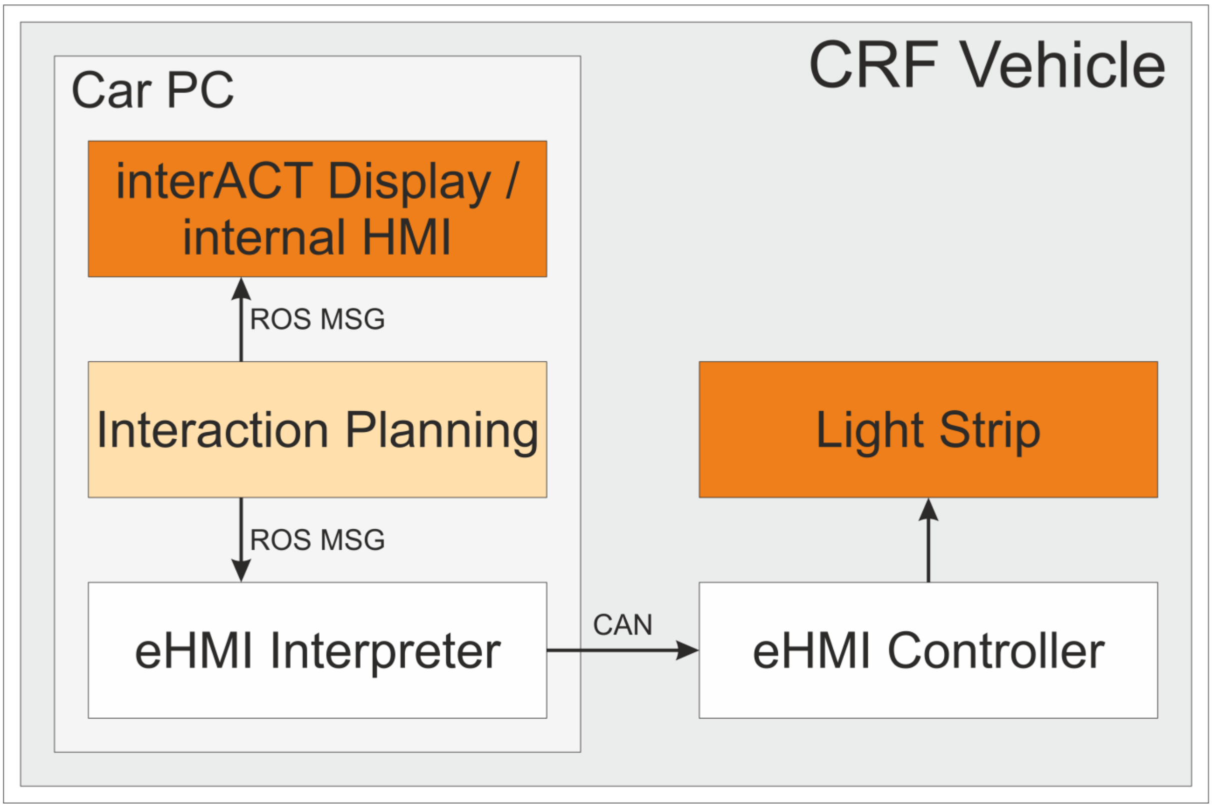


Figure 22: Interaction Planning control the internal HMI directly. The light strip is controlled via an eHMI interpreter that translates the native ROS messages to CAN messages for the eHMI hardware controller.

The Interaction Planning module was developed, based on simulated data and interface definitions. These simulated inputs had certain properties. They represent a controlled environment with perfect sensors and sensor data interpretation. The data is stable and continuous, e.g. there are no big jumps in position, no changes in object classification and no changes of identifiers of the objects. In this environment, Interaction Planning performed well, planning interactions and following the plan unless major changes in the situation occur. However, the jump from simulated data to real world data was significantly larger than expected. Instable object classifications and object identifiers caused problems when tracking situations and actors. As a result, the outputs of several components became rather volatile, e.g. Situation Matching reclassified situations several times within a second. Similarly, Interaction Planning had to cancel and recalculate plans whenever the situation changed, making the planned behavior or the AV more volatile and indecisive over the duration of the interaction than

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intended. Single planning instances still show reasonable plans, but there is much less continuity over time. In that regard there are still improvements to be made.

3.5 Validation of Trajectory Planning

As described in D3.2 and D5.2, the Trajectory Planning (TPL) Module is based on the Model Predictive Control (MPC) strategy: starting from the kinematic model of the vehicle, it is able to predict the future feasible trajectory until the maneuver destination. Moreover, it computes the optimal control inputs necessary to follow this trajectory, satisfying the environment constraints and actuators limits.

In particular, the proposed control is composed of two linear MPC, one for lateral dynamics and one for the longitudinal. The MPC, covering lateral dynamics, is based on a linear model obtained by applying an input-output transformation and controlling the states (the lateral displacement and the bearing of the vehicle) thorough the input *(the steering wheel angle).* The second MPC, covering longitudinal dynamics, is based on a "model particle" system obtained by increasing the system states and controlling the states (the longitudinal displacement and the speed of the vehicle) thorough the input (the acceleration). This MPC strongly depends on the output of the first MPC: the computed acceleration profile will depend on the predicted trajectory curvature (all implementation details are illustrated in D3.2).

For validation purposes, since the CRF demonstrator is focused on the parking scenario, the following test-site was chosen:

Figure 23: parking scenario for the validation of the Trajectory Planning module, as implemented on the CRF car. The area is the CRF employees parking. The reference trajectory to follow is coloured in RED.

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As shown, the illustrated scenario is represented by the parking area of CRF employees, along which the CRF car was able to move. It is worth to noting here that it is a real-world scenario, including two consecutive "U-turns".

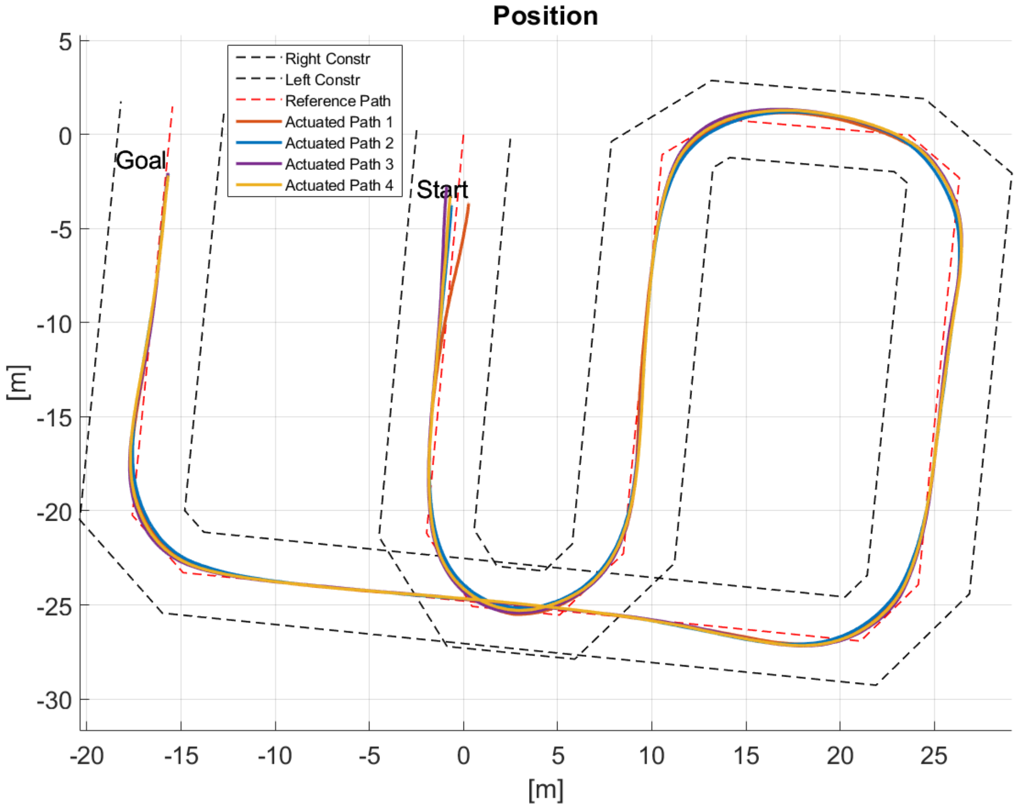

Figure 24: reference path vs. actual path of the vehicle, including different trials with different starting point.

The figure above shows the position (x,y) of the CRF vehicle on the test-site illustrated in Fig. 17. In particular, there are the right and left constraints representing the edges of the road and the reference path (RED dashed line). Then the continuous lines of different colours represent several trials of the actual path of the vehicle, with different starting points. For more details, a single path is illustrated in the following figure:

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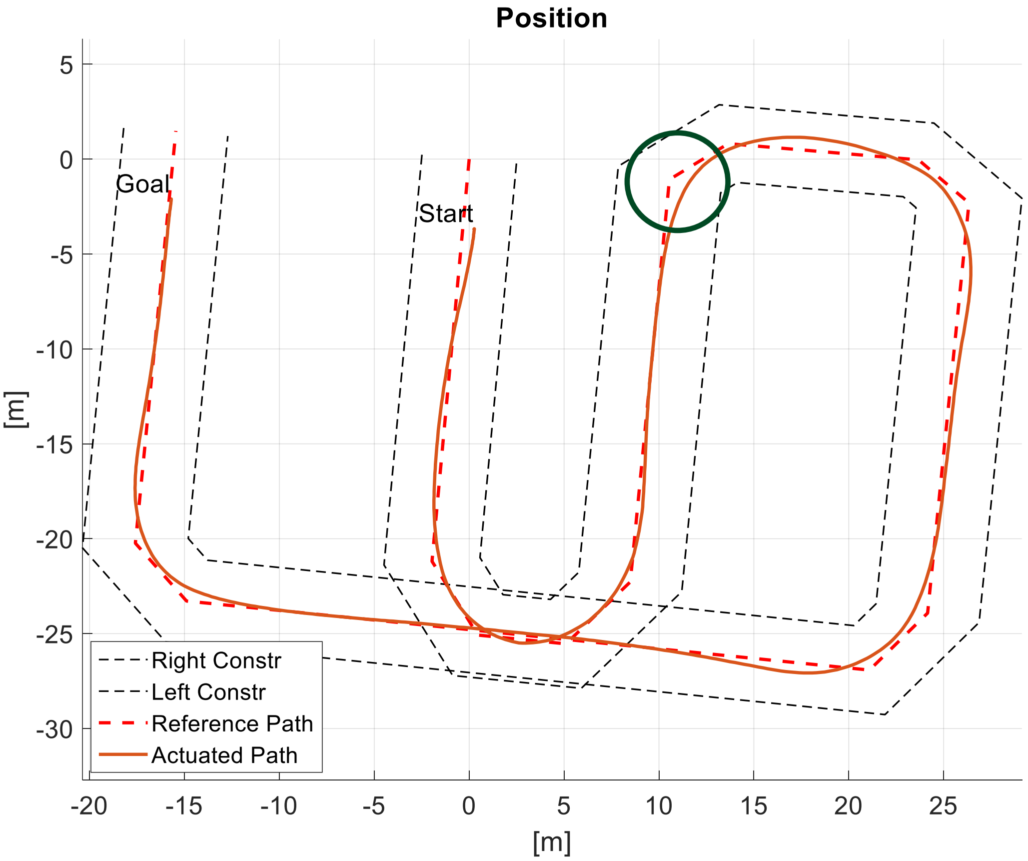

Figure 25: single trial of CRF vehicle actual path (continuous line) vs. reference path (dashed line), showing also the left and right constraints.

The vehicle control is able to actuate a smooth trajectory, even if the reference path is a broken line.

The following two figures show the error, for the multiple positions and for the single position, respectively:

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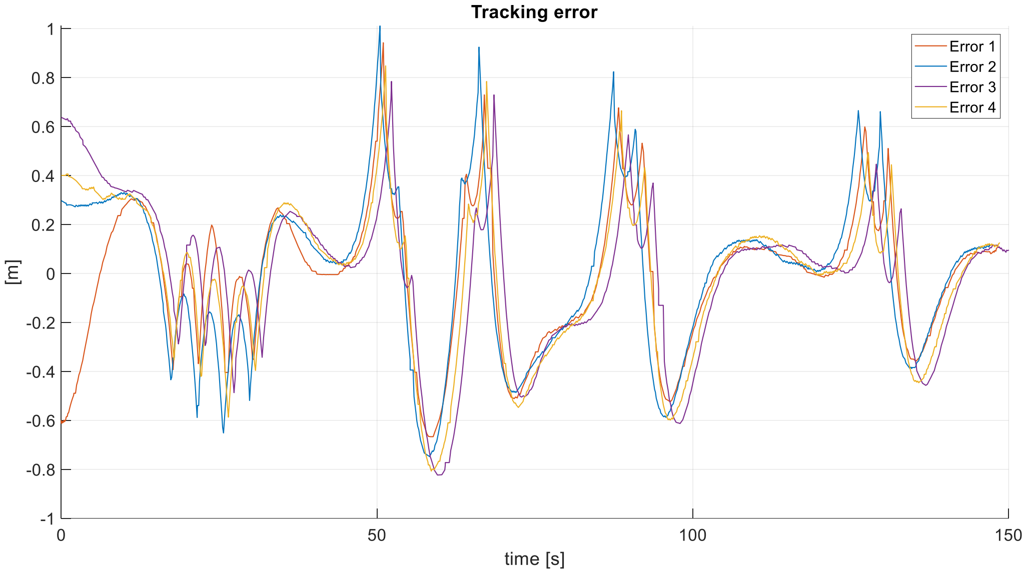

Figure 26: tracking error for the different paths, showed in figure 17.

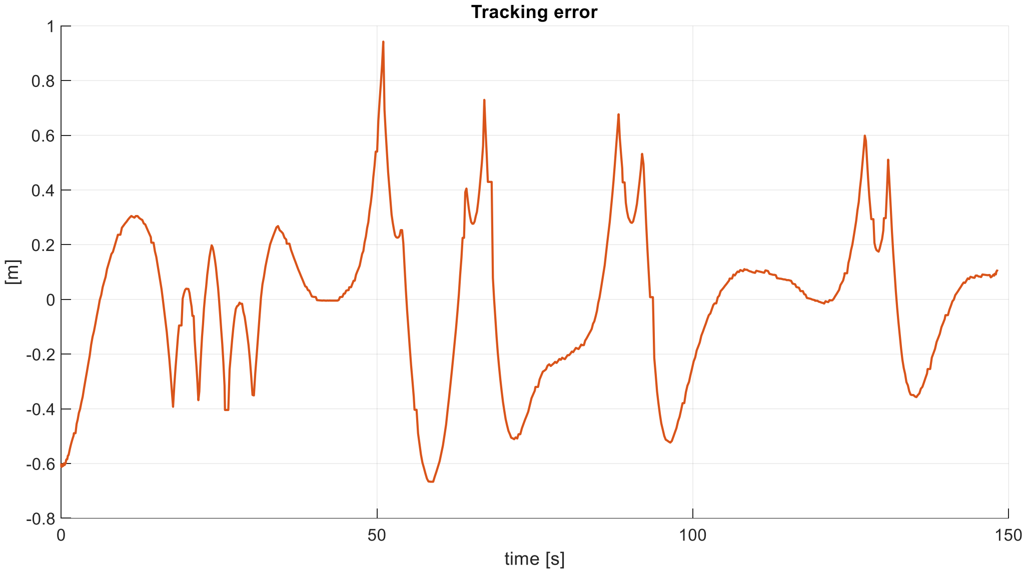

Figure 27: tracking error for the single path, showed in figure 18.

The maximum error is around 1m, corresponding to the corner/angle of the reference path (see the GREEN circle in Figure 24), otherwise the control is perfectly able to follow the reference trajectory and, in the corners, it is able to perform a smooth trajectory, following the physical limits of the vehicle dynamics and assuring the comfort of vehicle occupants.

Finally, similar results are confirmed for the steering angle profile (steering angle vs. time):

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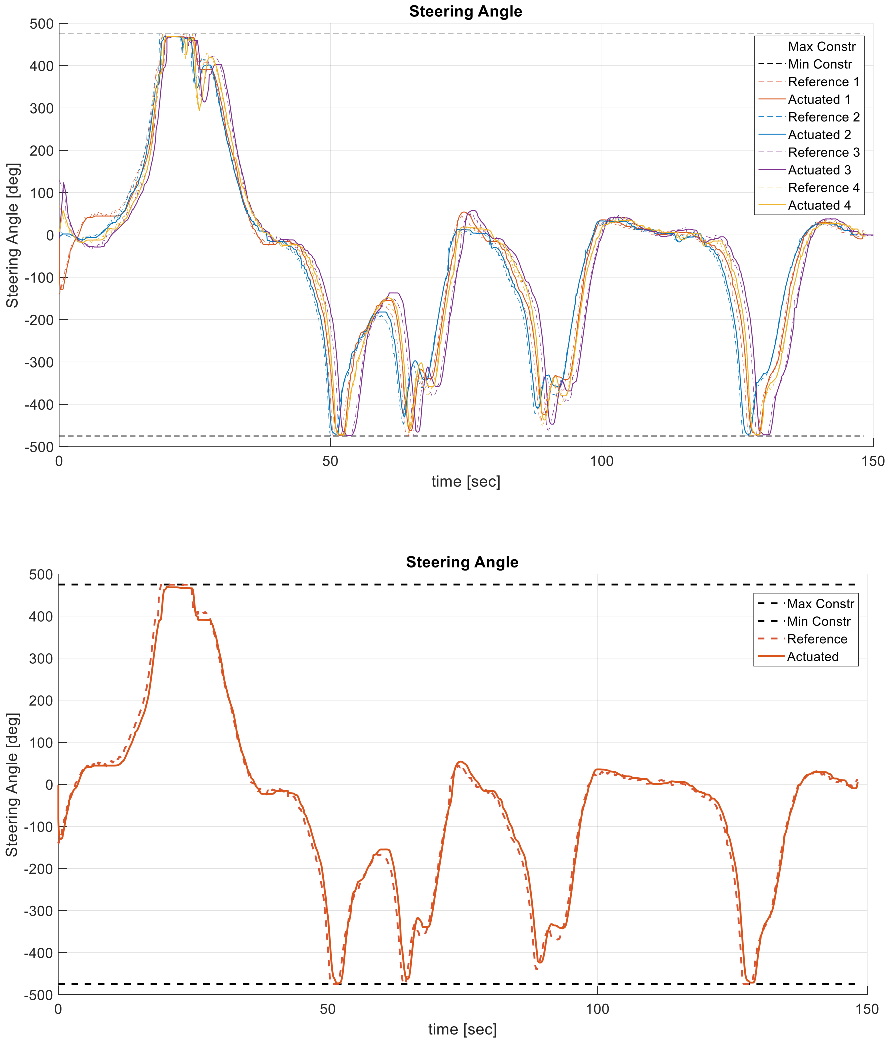
Steering Angle

a)

Steering Angle

b)

Figure 28: steering angle as function of time, for all the paths (figure a) and for a single path (figure b).

In figure 27, the maximum and minimum constraints are illustrated ("Max Constr" and "Min Constr", respectively) representing the physical limits of the steering actuator: as stated at the beginning, the MPC never perform request not physically acceptable. In addition, the actuated path is able to follow the reference one, making the profile smoother, especially in the discontinuity points.

Thus, to sum up, the control algorithm is robust with reference to the different starting positions and reliable with the different repetitions.

3.6 Validation of CCPU

In this section, a description of the validation procedure of CCPU as a whole is provided.

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3.6.1 CCPU architecture and updates from previous deliverables

The Cooperation and Communication Unit (CCPU) acts as the brain of the interACT system and is responsible for orchestrating the interactions of the Automated Vehicle (AV) with the other traffic participants (TPs). By analysing the current and predicted behaviour of other TPs, it develops an expectation-conforming, safe plan for the future motion of the AV.

A systematic analysis of CCPU's modules was presented in **D3.1** [5] (concept description) and **D3.2** [3] (internal components and communication). Component integration and fine tuning was performed, as part of WP5's work. After few required modifications, the final version of the CCPU architecture is depicted in **Figure 29**Fehler! Verweisquelle konnte nicht gefunden werden.**.**

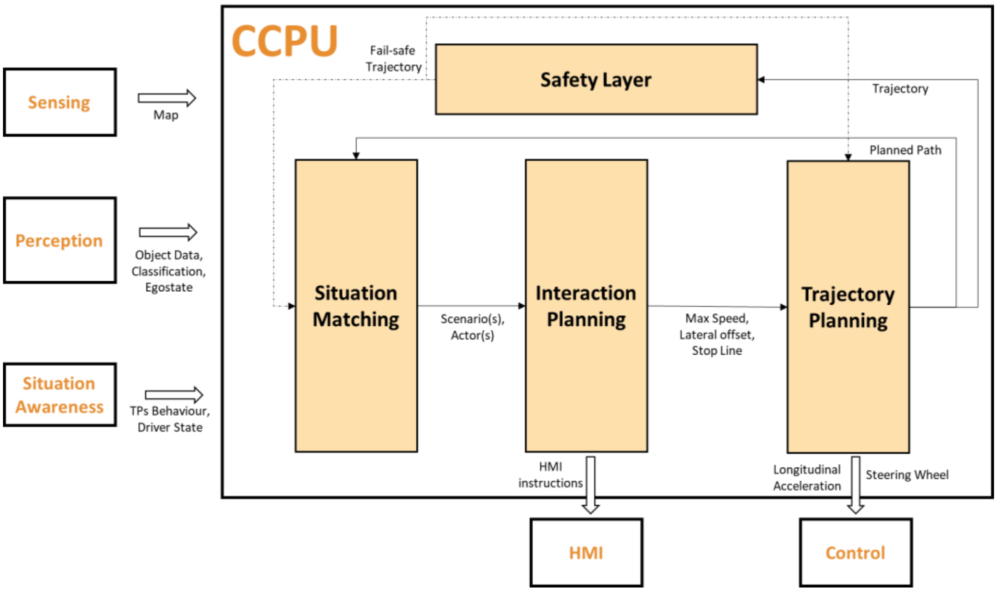

Figure 29: CCPU architecture

This accounts for the modifications that needed to be done, in order to enhance system stability and performance, under real-time constraints. These modifications included:

- Parity checks to detect malfunction of sensor data; namely GPS signal loss and ghost effects in object detection.
- Communication frequency threshold management to allow for easier synchronization and communication between the components and minimize jittering effects (sudden variations in component output).
- Map refinements to correct map inconsistencies and other errors related to object positioning.
- Redirection of the safety layer's output to the trajectory planner, given the emergent safety requirement that only the trajectory planner will be in charge of handling the actuators.

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3.6.2 End-to-end Simulation Results

Validation of the end-to-end functionality of the CCPU was conducted during the whole development and integration phase (WP5). The testing included the following phases:

1. Individual component unit testing [3]
2. End-to-end system and communication testing using dummy (simulation) data [3]
3. End-to-end system testing using actual recorded data (Abstaat, Orbassano premises).

Focusing on the third step, and in order to increase the size of the datasets for testing, scenario variations were generated in simulation.

Details on the validation of the CCPU output with respect to the rest of the interACT system has been presented in **Sec**. Fehler! Verweisquelle konnte nicht gefunden werden. (AV interaction strategy e valuation) and **Sec.** Fehler! Verweisquelle konnte nicht gefunden werden. (AV trajectory planning evaluation), whilst in **Sec.** Fehler! Verweisquelle konnte nicht gefunden werden. we have shown a proof of concept of the CCPU internal logic and in particular on the AV-to-traffic conflict detection (and subsequent situation matching), which constitutes the CCPU process triggering condition.

3.6.3 On-vehicle Proof-of-concept and Final Event preparation

The results described in **Sec. 3.6.2** were cross-validated using the in-vehicle components during the 2nd and 3rd integration meetings, in CRF premises (Orbassano, Turin). In essence, this second round of on-site validation aimed to ensure system interoperability, as well as to verify the deployment process of the various software modules.

From a practical point of view, using Docker containers [1] end-to-end in the interACT toolchain has proven the advantages of virtualization, as a proof of concept, namely:

- Rapid and easy deployment, since all is needed is a stable internet connection.
- Security, because the vehicle's internal network is isolated.
- Compartmentalization, given that each module is installed and runs independently.
- Continuous development and upgrade, as software updates from one source do not require end-to-end modifications and re-installations.

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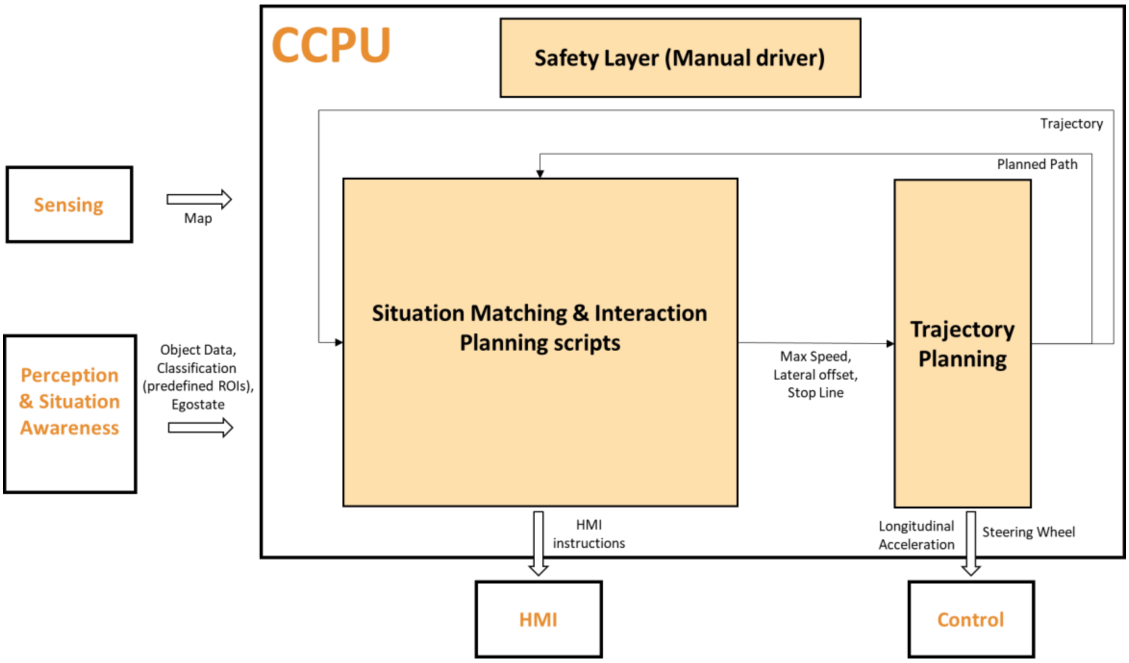

Figure 30: Partial CCPU architecture

During the 4th Integration Meeting at CRF, the demonstration vehicle was prepared for interACT's Final Event exhibition. Also, the final demonstration scenarios were decided, as presented in **Figure 25**Fehler! Verweisquelle konnte nicht gefunden werden. **(AV to pedestrian crossing)** and **Figure 26**Fehler! Verweisquelle konnte nicht gefunden werden. **(AV to vehicle crossing)**. During the experiments, the CCPU was partially active as depicted in Fehler! Verweisquelle konnte nicht gefunden werden. **Figure 24**, in an effort to maximize automotive functional safety, in terms of avoiding potential collisions as a result of system malfunction. The results are discussed in **Sec.** Fehler! Verweisquelle konnte nicht gefunden werden..

Two more sets of real-time tests had been expected to be carried out in BMW premises in Maisach: pre-tests on March 17th-19th and pre-demo tests on March 30th–31st, but due to the COVID-19 pandemic, all such activities were suspended.

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Figure 31: Torino snapshot - Representation of a pedestrian scenario. (a) Potential conflict between pedestrian (red) and AV (dashed yellow) trajectories. (b) AV detects the scenario and decides to stop (yellow stopline). (c) Pedestrian continues his route (HMI green led indication is on). (d) Route is no longer blocked. The AV is safe to continue. HMI led is off.

Figure 32: Torino snapshot - Representation of a vehicle scenario. (a) Potential conflict between turning vehicle (red) and AV (dashed yellow) trajectories. (b) AV detects the scenario and stops (yellow stopline). (c) White vehicle completes its turning. AV's HMI green led indication is active for the duration of the conflict. (d) Route is no longer blocked. The AV is safe to continue. HMI led is off.

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The next section provides an overview of possible future research on CCPU, based on the “lessons learnt” in interACT project.

3.6.4 Future Work

While the preliminary results have shown that the CCPU can detect traffic scenarios with a relatively high accuracy, there are certain issues which should be taken into consideration, to ensure system stability and enhanced performance.

- Sub-modules’ Communication Scheme
  As discussed in [5], ROS was chosen over other communication protocols, because it is proven as a suitable mechanism for low-level communications, mainly in embedded (robotics) systems. While its solid structure and user-defined messages allow for easy inter-component communication and testing, the overhead introduced due to its internal mechanisms causes delays both during the development phase and during runtime. Identification of other messaging schemes (ex. LCM) [6] would be beneficial in order to minimize delays.

- Sensor inconsistency
  The high dependency of all CCPU modules on sensor data, makes the use of high-sensitive sensors increasingly important. As a future recommendation, it seems that current hardware is not mature enough for sensitive real-time applications and hence redundancy combined with sensor fusion techniques should be investigated.

- Virtualization
  Virtualization offered by the adopted Docker technology has proven to be helpful in regards to fast deployment and dependency reduction between the components. As the system scales up and multiple components are running, Docker becomes greedy in system resources, often causing crashing problems. A solution towards virtualization orchestration (ex. Kubernetes [7]) should be investigated for a CCPU-alike system real-time deployment.

- Timing issues
  Currently, the execution time update rates achieved by the CCPU prototype is not comparable with embedded automotive applications (e.g. for almost real-time apps less than 100ms is expected). There are several upgrades that need to be done to vastly increase time performance, both hardware-wise (car PC memory and CPU) and software-wise (minimize redundant inter-component calculations, use of orchestrator, etc.)

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4. Test Results of interACT System in CRF Demonstrator

With reference to Section 2.2, Figure 4, in this section we highlight the main results achieved by the interACT system, fully implemented on CRF demonstrator, including the integration of the Perception Platform (PP) and the Communication and Cooperation Platform Unit (CCPU).

As a reminder, the scenario represents a parking area, where the CRF demo has to interact with pedestrians and other vehicles. In particular, the interaction with pedestrians is the goal of the evaluation in WP6 and it is described in the deliverable D6.2; here, we focus on the interaction with another vehicle. The tests are executed in the private FCA test-track (see section 2, figure 5).

Five runs have been performed for each test-scenario. For the sake of readability, only one plot is reported here in the document.

4.1 System Behaviour in dedicated Scenario 1

In scenario 1, the CRF demo-vehicle is travelling straight on and another vehicle is coming from the right side, with the intention to turn on the left.

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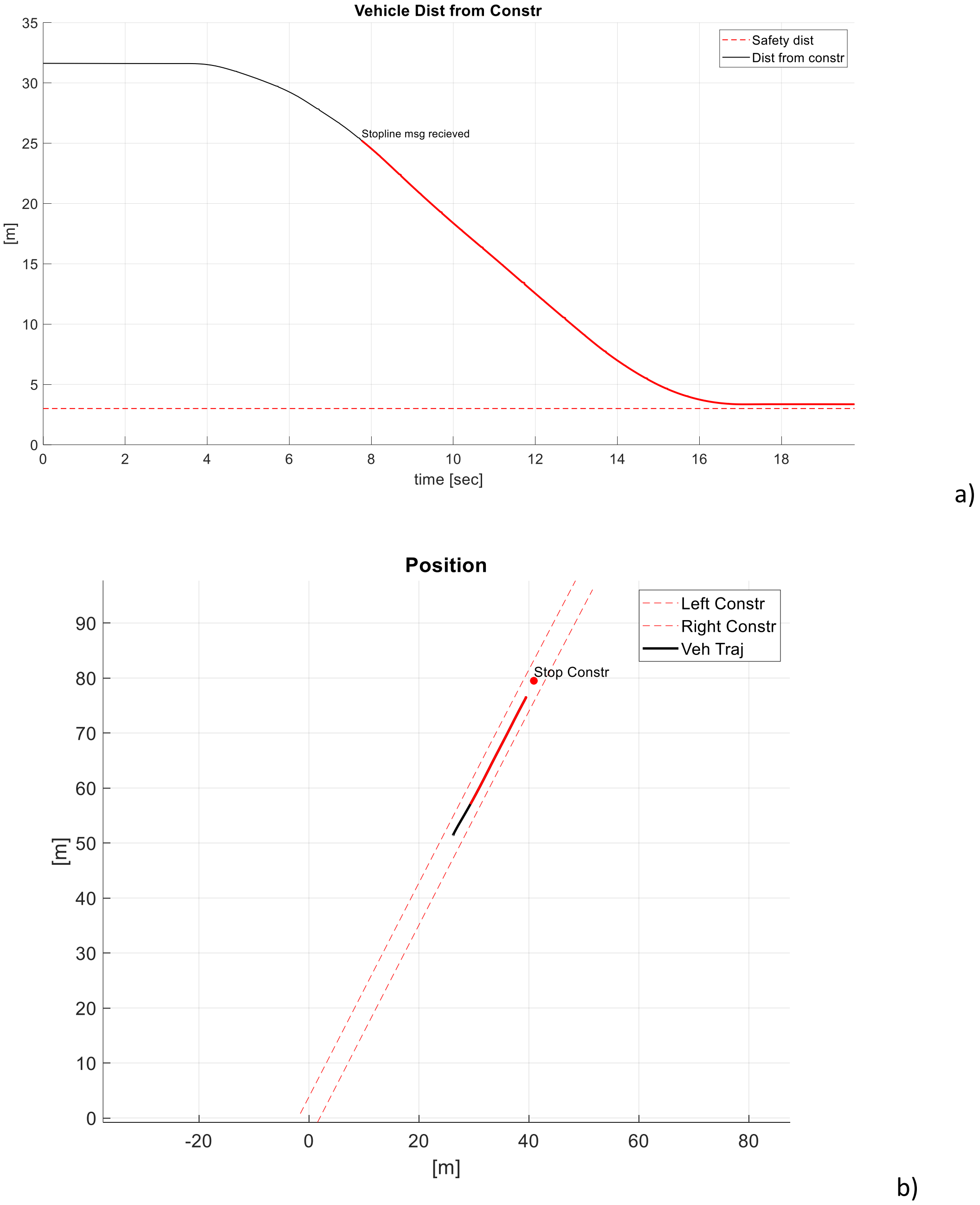

Figure 33: vehicle distance from constraints as function of time (fig. a) and vehicle position as function of time (fig. b).

The CRF vehicle is able to stop within the constraints (in terms of distance and deceleration), provided by the CCPU, giving way to the other vehicle.

4.2 System Behaviour in dedicated Scenario 2

Even more interesting is the second scenario, where the CRF vehicle is turning to the left, while another vehicle is travelling straight on, from the left side.

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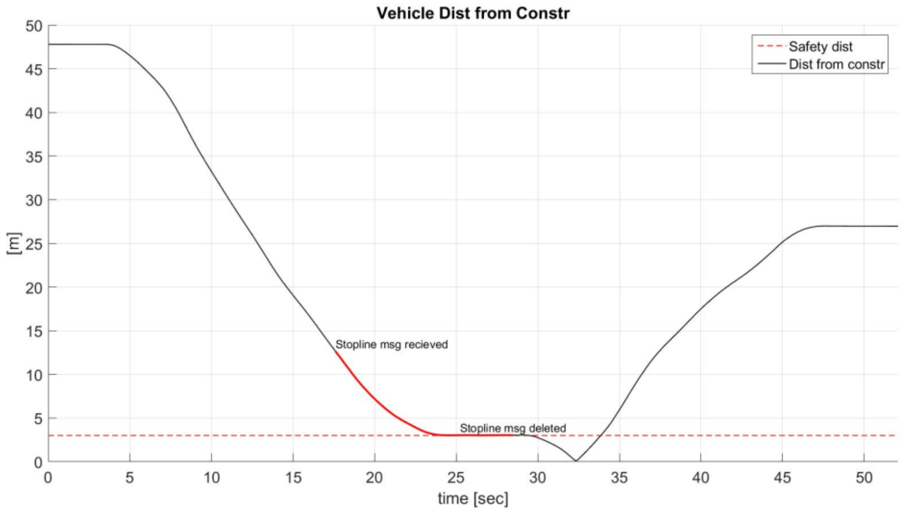
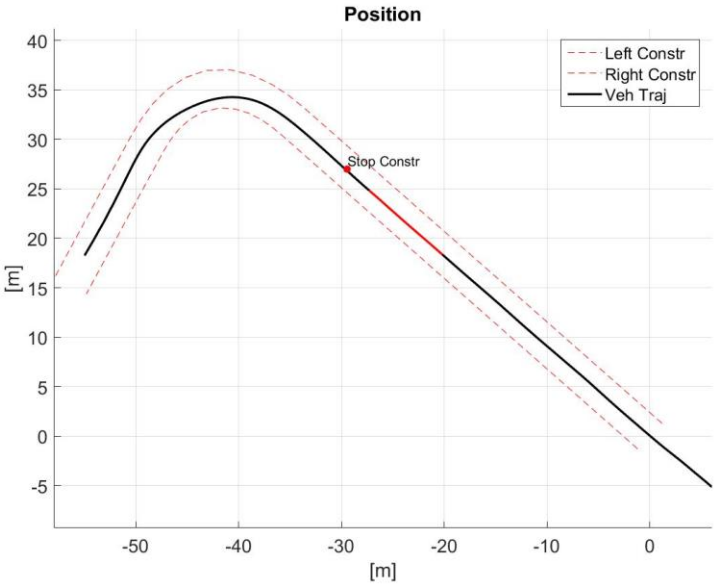
The same figures are illustrated below:



a)



b)

Figure 34: vehicle distance from constraints as function of time (fig. a) and vehicle position as function of time (fig. b).

The CRF vehicle is able to stop within the constraints, giving priority to the other vehicle; then, the CRF vehicle can start again (to complete the maneuver of turning left).

In addition, for this test-case, we can show also the speed, acceleration and jerk as function of the time:

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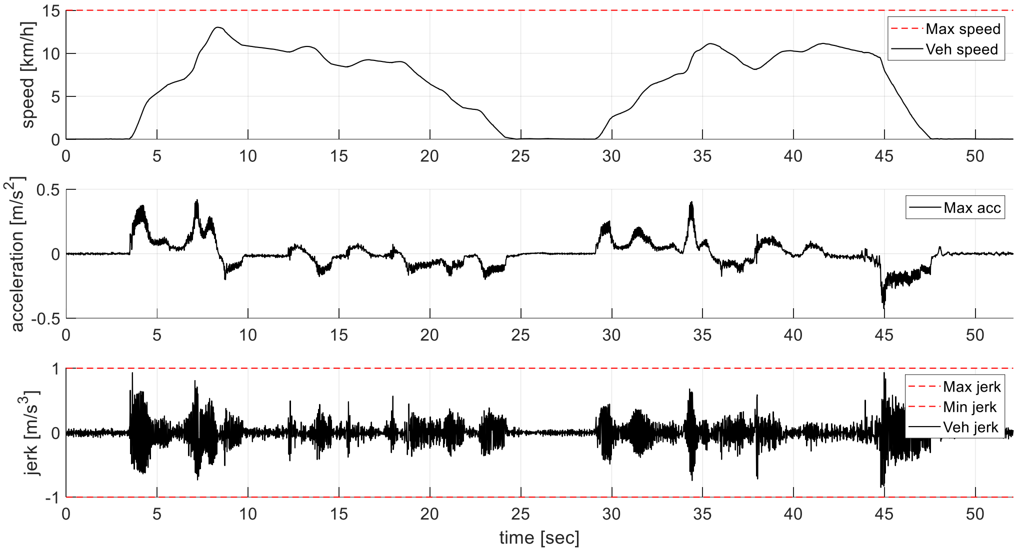

Figure 35: speed, acceleration and jerk as function of time, for scenario 2.

As sketched in the figure, the CRF vehicle satisfies all the constraints provided by the CCPU, representing the interaction strategies between the host-vehicle[2] and the obstacle[3]. In particular, the maximum allowed speed is 15 km/h and the acceleration is in the range [-0.5 0.5] m/s^2. Also the jerk is within the maximum and minimum values (1 m/s^3 and -1 m/s^3, respectively).

4.3 Short Description of Pedestrian Scenario

As aforementioned, the details for the pedestrian scenario are described in D6.2 (from WP6). Moreover, this scenario is similar to scenario 1 (interaction of the CRF vehicle, travelling straight on, with another vehicle moving straight forward from the left). In this paragraph, a brief overview is anyway provided.

The following figure sketches this scenario:

---

[2] Host-vehicle is the vehicle installing the interACT system (in this case, the CRF demonstrator).

[3] The obstacle is the other vehicle, moving in the same scenario.

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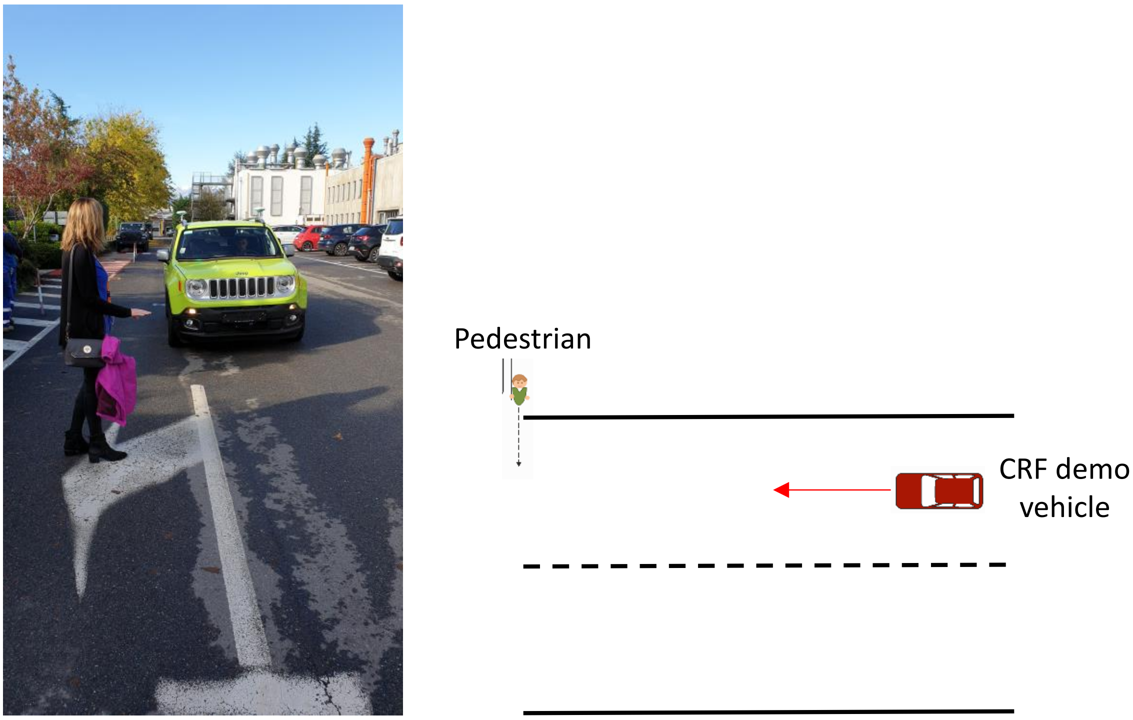
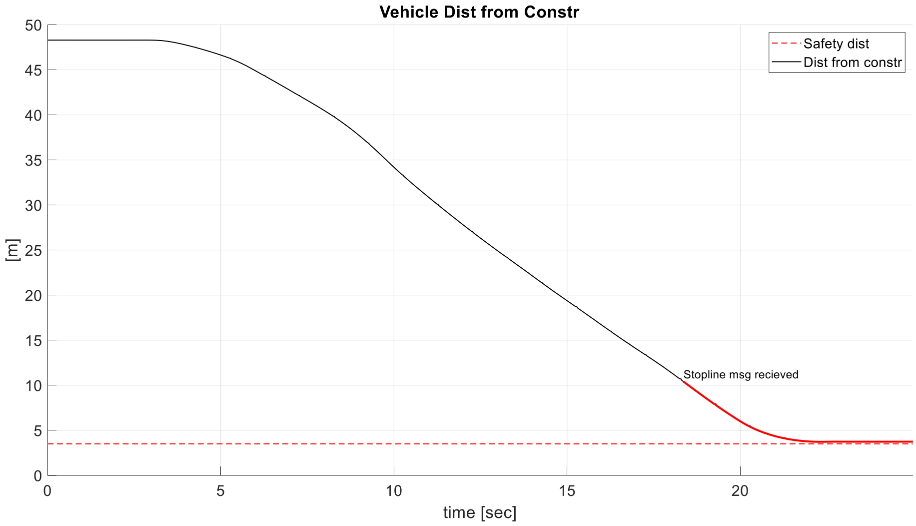


Figure 36: sketch of the scenario, where the CRF car interacts with a pedestrian.

The main results are reported in the following figure:



a)

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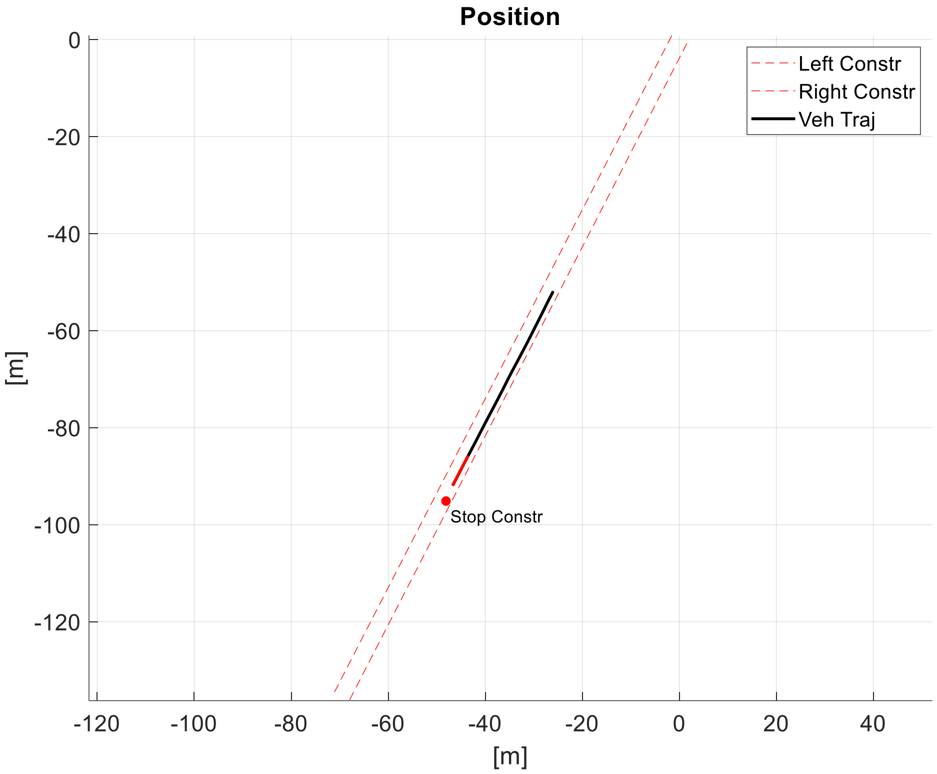

b)

Figure 37: vehicle distance from constraints as function of time (fig. a) and (x,y) position (Fig. b).

Also in this case, as in scenario 1, the CRF vehicle is able to stop within the constraints (in terms of distance and deceleration), as provided by the CCPU.

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5. Test Process of the BMW Demonstrator

This section provides the main results of the integration of the whole interACT system in the BMW demonstrator.

5.1 Introduction and baseline

The basis for the BMW interACT demonstrator is a BMW i3 series vehicle. Within WP5 the series vehicle has been equipped with fully integrated external HMI (eHMI) components to investigate the interaction between the vehicle and other traffic partners in an urban environment. The integration process as well as a detailed description of all additional components compared to the series car have already been reported within Deliverable 5.2 of WP5.

The Deliverable 5.2 also gives an insight into the test process and the individual tests during the integration phase. The complete test process of the BMW demonstrator is shown schematically in Figure 38.

Basically, the testing process of the BMW demonstrator is divided in two test sections:

1. **Component verification**: Test and validation of each single component, before starting the integration of the component and after the successful integration into the vehicle.
2. **System verification:** Test and validation of the entire system including all components, integrated in the vehicle.

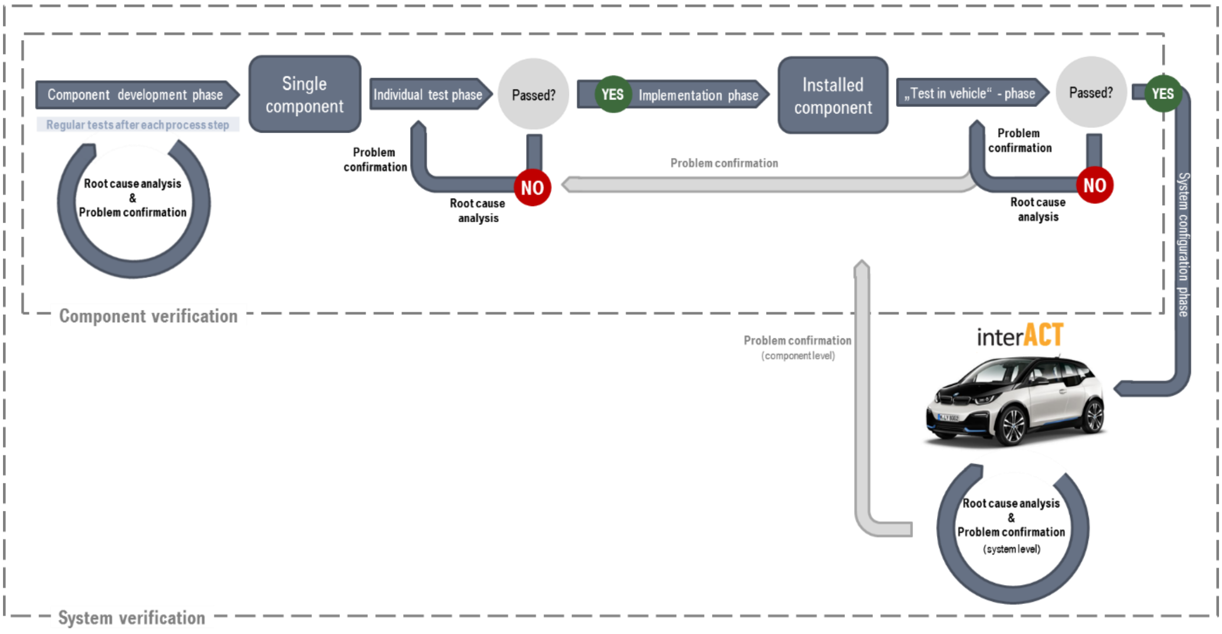

Figure 38: Test process of the BMW demonstrator

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The entire test process for the BMW vehicle has already started within the development phase of the components within WP4. During that phase, the components or rather the different parts of one component have been tested after each process step to create a fully developed “Single Component”. In our case, single components are not only parts which have been developed within the interACT project, but also purchased parts/components which were necessary to realize the interACT system in the demonstrator. In a first step, each single component has been tested before starting the integration process into the series car. Thereby, the functionality as well as the ability to be integrated (in form of mounting trails) have been verified. If all of these test were passed, the integration process, described within D5.2, was ready to be started. Otherwise, if problems were detected during the first tests, the root cause was analyzed and based on this investigation the problem was solved before repeating the test once more.

Following the integration of each component into the series BMW i3, the functionality of that component was tested once more. Again, potential errors were investigated and subsequently solved. After the successful integration and subsequent test of all individual components, the entire system was configured and the behavior of all components to each other in the BMW demonstrator was tested. In a first step, the system verification took place in the BMW body shop under constant environmental conditions (lab conditions). Depending on the root cause, any problems that were raised during the system validations have been rectified on a system- or component-level. Subsequent to the successful tests of the interACT system in the BMW demonstrator under lab conditions, the test of the entire system in the BMW demonstrator was repeated outside under real environmental conditions on a test track.

The testing phase for the WP6 evaluation studies was started only after faultless tests of the entire system under lab conditions as well as under real environmental conditions.

5.2 Component verification under lab conditions

In Deliverable 5.2 the components integrated in the BMW demonstrator, are already described in detail. A summary of the main components and a brief description is shown in Table 4.

System	Components	Relation	Description
eHMI	360° light- band	WP4	eHMI component for 360° intention and perception based interaction
	Signal lamp	WP4	eHMI component for perception based interaction
	eHMI ECU & eHMI control panel	WP4 + WP6	Control unit for both eHMI components
	GPS antenna	WP6	Antennas to receive GPS signal

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	OxTS RT3003	WP6	System to create current vehicle data such as position and velocity
	OxTS RT Range	WP6	System to create vehicle data in relation to an object
	NTRIP modem & GSM antenna	WP6	Modem and antenna for the correction of the GPS signal
PC	Computer for data collection “Spectra PowerBox”	WP6	PC logging all vehicle and interaction data as well as video data for detailed analysis of interaction patterns in evaluation studies
Cameras	Axis F1015	WP6	Cameras to monitor the surrounding during the studies

Table 4: Summary of the main components in the BMW demonstrator

As described in Chapter 5.1, the individual components have been already tested and refined during the development phase of WP4 as well as during the integration process. All components have been verified under constant environmental conditions in the laboratories of HELLA as well as in the body shop of BMW. These tests have also been described within D5.2 in chapter 3.4 [16]. Table 5 shows a detailed overview of the tests on the component level during the whole test process.

System/ Comp.	Test-process phase	Type of test	Responsible partner
eHMI 360° light-band & Signal lamp	Component development phase	Simulation tests with CAD data of the vehicle to check the space requirements for the eHMI components and to ensure the assembly of the eHMI components	HELLA
	Component development phase	Optical simulation tests to check the photometric parameters of the eHMI components	HELLA
	Component development phase	Mechanical tests with the PU body parts (without any optical or electrical components) in form of mounting trails to check size accuracy and the assembly of the newly produced body parts	BMW
	Component development phase	Functional tests with the electrical and optical components of the eHMI components (without housing)	HELLA
	Individual test phase	Functional tests with the assembled eHMI components (electrical and optical components are integrated in the body parts / housing)	HELLA BMW

	Implementation phase	Mounting trails and functional tests with the final eHMI components during the Implementation phase	BMW
	"Test in vehicle" - phase	Functional tests of the eHMI components after completing the integration phase	BMW
eHMI eHMI ECU	Component development phase	Functional test of the eHMI ECU	HELLA
	Individual test phase	Functional test of the eHMI ECU in combination with the eHMI components	HELLA BMW
	"Test in vehicle" - phase	Functional test of the eHMI ECU after completing the integration phase	BMW
eHMI eHMI control panel	Component development phase Individual test phase "Test in vehicle" - phase	Software tests of the eHMI control panel	HELLA BMW
DGPS All components	Individual test phase	Functional tests of individual components and functional tests of all DGPS components together	BMW
	"Test in vehicle" - phase	Functional tests of all DGPS components together after completing the integration phase	BMW
PC Spectra Power Box	Individual test phase	Functional tests of the Spectra Power Box	BMW
	"Test in vehicle" - phase	Functional tests of the Spectra Power Box after completing the integration phase	BMW
Cameras Axis F1015	Individual test phase	Functional tests of the Cameras	BMW
	"Test in vehicle" - phase	Functional tests of the Cameras after completing the integration phase	BMW

Table 5: Tests on component-level for the BMW demonstrator.

After all individual components, as well as the individual systems (eHMI-, DGPS-, camera-system), were successfully tested in the vehicle, the whole system was configured before starting the verification of the entire interACT system in the BMW demonstrator.

5.3 System Verification

For the verification phase, we consider now two types of tests: in lab and on field, respectively described in the next paragraphs.

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5.3.1 Laboratory tests

The configuration of the entire system as well as the first verification of the system took place at the body shop of BMW under constant environmental conditions. As it is shown in Figure 39 [16], the PC (Spectra Power Box) is the core component which receives input from all other systems such as the DGPS-, eHMI- and camera system. Therefore, the data logging software has to be configured to ensure an overall analysis of the parameters in the evaluation studies in WP6. Additionally, the DGPS system has been set up to guarantee correct values of the vehicle-position, -velocity, -acceleration and time.

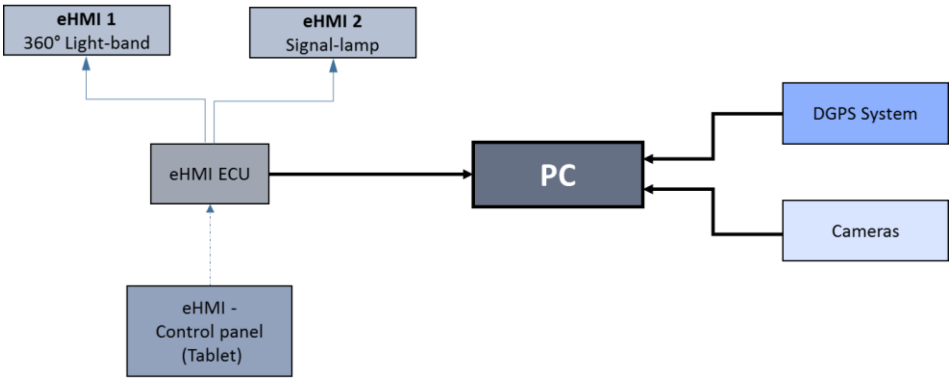

Figure 39: Schematic overview of all components in the BMW demonstrator.

Following the configuration, the entire system test was carried out statically at the BMW body shop. The main focus of these system verification under constant environmental conditions, was to test the functionality of the eHMI components in combination with all the other components, the practical applicability of the eHMI control panel and the reliability of the data logging software of the PC. Thereby, some minor issues with the logging software and the control panel were detected and subsequently adjusted.

5.3.2 Field tests

After the successful laboratory tests of the entire system, the BMW demonstrator was brought to a test track for further tests of the system under real environmental conditions (**Fehler! Verweisquelle konnte nicht gefunden werden.**). Naturally, the field tests focused on the functionality of the entire system under real environmental conditions (static state as well as dynamic state) but two issues were especially monitored:

1. Functionality and accuracy of the DGPS system in dynamic state (during a test-drive).
2. Functionality and behaviour of the eHMI components depending on environmental influences such as temperature, weather conditions or ambient brightness.

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Figure 40: Test of the interACT system and the eHMI components at the test-track.

The functionality of the entire system (including eHMI components) as well as the functionality and accuracy of the DGPS system have successfully been tested during several test-drives on the test track. Furthermore, the functionality of the whole system was tested with the specific scenarios during the study preparation and the data, logged by the PC have been analysed for test purposes.

In interACT, there was no time to test the eHMI components and the whole interACT system under different environmental conditions in climatic chambers in the laboratory, like it is done within the development process of components for a series car. In the case of the interACT project, the behaviour of the eHMI components and their environmental influences have been monitored during the test drives, the study preparation drives as well as during the WP6 evaluation studies. During this period, the vehicle and especially the new body parts with the integrated eHMI components were subjected to different environmental conditions such as temperature and humidity. Specific irregularities, which were detected during the test drives and the evaluation studies have been documented and were corrected immediately.

As the functionality of the entire system was tested successfully on the test-track, the vehicle has been handed over to WP6 for the evaluation studies of the BMW demonstrator.

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6. Test Results of interACT System in BMW demonstrator

The tests of the functionality of the entire interACT system in the BMW demonstrator didn't disclosed any inconsistences during the test drives, the scenario specific system verification or the WP6 evaluation studies. All components and systems ran without errors under real environmental conditions.

As mentioned in chapter 5.3.2, a main focus during the real world testing was on the behaviour of the eHMI components and their dependence on environmental influences. Thereby, no problems or inconsistences regarding the functionality of the eHMI components and all the other systems have been observed. During the first evaluation study in December, a mechanical issue had occurred and a crack in the windscreen was noticed. The crack occurred in the area of the adhesive points of the signal lamp on the inside of the windscreen. Based on this error pattern, the root cause analysis for the crack was clear. The extreme temperature differences (approximately up to 30°C) between the heated parking hall and the test site in combination with the activated "heated-windshield function" of the vehicle (to avoid fogged windows) resulted in tension between the laminar gluing of the signal lamp on the windscreen and the glass. As both components (glue and glass) have different expansion coefficients in case of temperature differences and the glue was applied along the whole adhesive surface, the extension of the glue resulted in the crack in the windscreen. After this mechanical problem was detected, the windscreen was replaced and the signal lamp glued only on adhesive points to the windscreen and not along the whole adhesive surface to avoid the tension. After this conversion measure at the body shop, study preparation and the evaluation studies could continue. As this mechanical problem didn't arise again, the countermeasures were successful.

As the functionality of the entire system was not affected by this mechanical issue and no further inconsistences were detected, the required documents have been prepared to apply for a special permit that allows to test the BMW demonstrator in real traffic environment (not only on test-track). Therefore, a special permit according to §70 of the "German Road traffic licensing regulation" (StVZO) was needed, because the eHMI components are additional lighting elements which are not included in the road approval of the series vehicle. For this special permit colleagues from TÜV and the Bavarian State Ministry of the Interior confirmed the legal permissibility of the eHMI components for study purposes in real traffic environments.

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7. Conclusions

The goal of the present document was to show the results of the integration of the interACT system (including enablers and components, as developed by WP2-4), as well as the technical verification (of the whole system) and validation (of the single modules). The basis is the work performed in WP5 of the interACT project.

In this perspective, this deliverable D5.3 illustrates the contributions of WP5 to the following project milestones:

- Milestone 6: "**interACT demonstrators ready for evaluation**" ⇒ Integration and functional tests on interACT components successfully completed and vehicles ready for evaluation.
- Milestone 7: "**interACT solutions evaluated and demonstrated**" ⇒ Demonstration of interACT solutions on demonstrator vehicles and simulators successfully completed at the final interACT event

This means that two vehicle prototypes were ready for evaluation (WP6) and for demonstration (initially foreseen in the final event in Munich, then canceled due to COVID-19 virus), prepared by CRF and BMW. They are sketched in the following figures:


a)
b)

Figure 41: final version of BMW demonstrator (Fig. a) and CRF demonstrator (Fig. b).

These two prototype vehicles focus on different aspects, as follows:

- *Demo use-cases*: urban intersection for BMW car; parking lot for CRF car.
- *PP and CCPU*: neither CCPU (just parts of it for eHMI control), nor additional sensors for BMW car; fully integrated and functional CCPU, completely integrated sensors for CRF car.
- *eHMI*; fully integrated and functional eHMI – LED stripe and directed single lamp, for BMW car; basic solution of eHMI elements (LED stripe) for CRF car.
- *Evaluation*: Wizard of Oz evaluation in real traffic for BMW car; on private test-track for CRF car.

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As lessons learnt, some key-points have to be taken into account for future activities in these topics:

- Need of high-precision digital maps and positioning (for trajectory planning in particular), as the ones used by the modules of the CCPU.
- Need for 360° surrounding view for detecting dynamic/static obstacles, such as the PP we integrated in the CRF vehicle.
- Careful design of external/internal parts of the vehicle, to take into account the integration of the sensorial system and eHMI components.

In addition, more work shall be done to reach higher TRL, both at the components level and at the global interACT system level.

Deliverable D6.2 provides more insight from WP6 evaluation, with focus on the studies on eHMI road-user acceptance and assessment of CCPU decisions on different traffic scenarios.

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Designing cooperative interaction of automated vehicles with other road users in mixed traffic environments