Advisory Warnings Based on Cooperative Perception

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Abstract—The Ko-PER (cooperative perception) research project aims at improvements of active traffic safety through cooperative perception systems. Within the project a prototype of a cooperative warning system was realized. This system provides early advisory warnings which are especially useful in critical situations with occluded conflict partners. The development process was accompanied by a series of driving simulator studies to determine both the potential to reduce traffic conflicts and important design characteristics of early advisory warning signals. The most important details of the prototype system’s components inter-vehicle information-fusion and situation analysis are described and the achieved warning timings are compared to the results of the driving simulator studies.

I. INTRODUCTION

Cooperative perception systems apply car-to-infrastructure and car-to-car communication, to enhance vehicle local perception with received information about the present traffic situation. By these means, a complete perception of the local traffic environment is possible. This permits the recognition of potential conflict situations more entirely and at a broader scale than it was possible using only vehicle local perception and to assist the driver at an early stage of conflict situations. For this purpose, suitable strategies for driver assistance have to be determined.

Sec. II provides a brief overview of related works and outlines the contribution of this paper. Within the Ko-PER project, a series of driving simulator studies has been performed [1-4], determining both the potential to reduce traffic conflicts and important design characteristics of early cooperative warning signals, see Sec. III. In this paper, a prototype of the cooperative warning system is described and tested on a public intersection in Aschaffenburg, Germany, see Sec. IV. The prototype system comprises several test-vehicles, equipped with localization-, perception- and communication-systems, inter-vehicle information-fusion (IV-IF), situation analysis, and an infrastructure perception system (IPS). The localization requirements for the described IV-IF approach are stated in Sec. V-A, accompanied by evaluation results of the IV-IF system, to give an indication of the available data quality. In Sec. V-B the realized warning timings of the prototype system are compared with the simulator timings in the scenario left-turn-across-path, see Fig. 1. Finally the robustness against false alarms is evaluated in Sec. V-C.

II. RELATED WORK

One aim within the Ko-PER project was to find a suitable strategy to forewarn drivers about potentially critical driving situations by so-called ’advisory warnings’ (see Sec. III). Here, the predevelopment of the warning concept took place within a series of driving simulator studies [1-4]. Although other research has previously investigated different aspects of cooperative driver warnings e.g., [5]-[7], the implementation and testing of these warning concepts into a real-world setting like in the present paper was mainly a non-issue.

This paper provides an evaluation of advisory warnings generated by a prototype system based on cooperative perception and a comparison with the results of a driving simulator study. To the knowledge of the authors there exist no further publications with a comparable setup.

In the past a large number of research programs addressed information interchange between vehicles and infrastructre-systems, see [14] and [15]. The main concept for IV-IF for active road safety applications within these works, is to make use of sender related localization and dynamic information as described in [22] and [21]. In this work, vehicle- and intersection-perception information is additionally communicated and incorporated into an extended environment model via IV-IF. This further enhances the information base for active road safety applications. Preceeding works were realized in the INTERSAFE-2 project but incorporated only intersection-perception information, [18]. Accompanying works within Ko-PER address the propagation of localization estimate uncertainties in the IV-IF transformation step, [19] and the refinement of the relative localization estimate within the IV-IF association step given a sufficient number of common perceived objects, [20]. With respect to the related works, the IV-IF-System described in this paper...
is state of the art and evaluation results are given to provide an indication of the accuracy grade of the system.

For the purpose of situation assessment various methods have been studied in the recent years [30], [31]. Especially for incorporating topology and geometry information of a digital map in the estimation of driver intention [32], [33], [34], as well as for accurate global positioning in intersections and lane identification [35], Bayes Networks (BN) have been successfully applied. Our approach profits from the advantages of Object Oriented Bayes Networks (OOBNs) when it comes to dealing with many interrelated (networking) road users, which represent a big combinatorial challenge in the interpretation of intersection situations. Moreover OOBNs allow a consistent knowledge representation, including the context dependencies, like traffic rules, priority, as well as mimicking of human reasoning about the development of a situation. Finally, BN enable a proper handling of uncertainties in measurements and sound combination of heterogenic data.

III. DRIVING SIMULATION

A. Warning Concept

Established assistance concepts in impending conflict situations that are mainly based on vehicle on-board sensors are considered to display urgent crash warnings or, if necessary, autonomously intervene with the operation of the vehicle [8], [9]. The objective of these urgent warning signals is to provoke the initiation of immediate brake or steering reactions by the driver (referred to as imminent crash warnings [10]). Due to cooperative perception, the time frame prior to these imminent driver warnings is accessible by displaying so-called advisory warnings [10], [11]. These warning signals are intended to draw the attention of the driver to emerging conflicts and generate a readiness to respond [11].

B. Human-machine interface and simulation results

In regard to the design of the human-machine interface, a series of driving simulator studies has been performed. In an extensive study comprising a large variety of different driving scenarios it has been shown, that these advisory warnings have a high potential to reduce traffic conflicts, especially if traffic conflicts are hard to anticipate and if the conflicting road users are occluded [1]. Regarding the effectiveness of advisory warnings, displaying the location in which the conflict is imminent has been shown to be of minor importance in comparison to warning timing. However, user acceptance may be increased by using direction specific warnings [2]. Finally, the optimal timing of advisory warnings has been determined. Advisory warnings should be presented as late as possible; however, they must be provided as early as needed in order to initiate an adequate response of the driver. In [3] it has been shown that if the driver receives visual-auditory warnings one to two seconds prior to the latest possible warning time (i.e., at a TimeToBreak of two to three seconds), conflict situations can be mitigated substantially. An overview of the simulation results pertaining to the human-machine interface was presented in [4].

C. Scenario implementation

For the present study, the geometry of the public test intersection has been rebuilt in the driving simulator of the Wuerzburg Institute for Traffic Sciences (WIVW), including the lane geometry and the respective traffic light cycles, see Fig. 2. The left turn driving scenario described in the preceding sections has been implemented: during a left turn maneuver the ego-driver is confronted with an oncoming vehicle which is suddenly appearing behind a truck that is oncoming and performing a left turn. The driver triggered the start of the conflict situation: the conflicting vehicle was accelerated from the occluded position when the driver passed a checkpoint. During the approach to the joint conflict point, an advisory warning was presented one second prior to the latest possible warning timing (i.e., two seconds prior to the last possible time to avoid a crash by braking) in accordance with study results described in the preceding paragraph.

IV. PROTOTYPE SYSTEM STRUCTURE

The advisory warning is generated by a situation analysis module, Sec. IV-E. The input for the situation analysis module is an environment-model provided by an inter-vehicle information-fusion (IV-IF) module. This module fuses perception data from the ego-vehicle with received localization- and perception data from other vehicles and an infrastructure perception system (IPS). The localization- and perception data is communicated via ITSG5-Hardware developed in simTD [17]. The used subsystems for the prototype are described in the following.

A. Localization and Perception

The used test-vehicles are equipped with RTK-GNSS-IMU-based localization-systems. The conflict partner is perceived by an intersection perception system (IPS) and a following test-vehicle. Detailed information on the IPS can be found in [12] and [13]. The ego-vehicle is equipped with a laserscanner-video fusion system. The test-vehicle serving as conflict partner is not equipped with a perception system in order to test the heterogeneous level of equipment. Two test-vehicles are used alternately to generate additional perception information by following the conflict partner. These vehicles are equipped with radar-only and a radar-video fusion perception systems. All systems use GPS receivers to synchronize the clocks used for sensor data time-stamping and data logging to the UTC timebase.
state | EIS PDO
---|---
position | $[\phi \; \lambda \; h]^{\text{T}}_{\text{ebE}} \begin{bmatrix} \dot{r}_x \\ \dot{r}_y \end{bmatrix}_{\text{EBOR}}$
velocity | $[v_x \; v_y]^{\text{T}}_{\text{ebE}} \begin{bmatrix} \dot{\psi} \; \phi \; \theta \end{bmatrix}_{\text{EBOR}}$
acceleration | $[a_x \; a_y]^{\text{T}}_{\text{ebE}} \begin{bmatrix} \dot{r}_x \\ \dot{r}_y \end{bmatrix}_{\text{EBOR}}$
orientation | $[\phi \; \theta \; \psi]^{\text{T}}_{\text{ibk}} \begin{bmatrix} \dot{r}_x \\ \dot{r}_y \end{bmatrix}_{\text{EBR}}$
angular rate | $[\phi \; \theta \; \psi]^{\text{T}}_{\text{ibk}} \begin{bmatrix} \dot{r}_x \\ \dot{r}_y \end{bmatrix}_{\text{EBR}}$

**TABLE I**
DYNAMIC STATES IN EIS AND PDO

B. Nomenclature

To use a communicated variable properly, it is essential to know its exact definition. Therefore a nomenclature common in the field of navigation systems is used in the following sections to state all variables with their reference- , object- and resolving-frames [24]. The used abbreviations are e for the earth-frame, b for the body-frame and n for the navigation-frame (East North Up (ENU) is used throughout the paper). The extra letters E, O and R refer to the ego-vehicle, the sender, and the reference point of a perceived object. Direction Cosine Matrices C are used to describe rotations. Parameters with the suffix 84 are standard-parameters of the WGS84 reference ellipsoid [24].

C. Communication

The message family used by the prototype system is called cooperative perception Message (CPM) with the variants iCPM and vCPM for infrastructure and vehicle perception systems. The CPM contains two main substructures the Ego Information Structure (EIS) and an array of Perceived Dynamic Objects (PDO). It is sent with a constant rate of 10Hz. The EIS contains an UTC-referenced timestamp, the dynamic state and the size of the ego-vehicle. The timestamp is valid for all data in the CPM. A PDO contains the dynamic data1, an ID, a reference point and the objects size. The dynamic states of EIS and PDO are listed in Tab. I. The dynamic state is assumed to be Gaussian-distributed. For further details on the specification see [16].

D. Inter-Vehicle Information-Fusion

The objective of the inter-vehicle information-fusion (IVIF) is to create a consistent set of dynamic objects in the ego-vehicle’s surrounding based on the information contained in received and local CPMs. It is assumed that there is only one track per object and false alarms are sufficiently suppressed by the sender. The received objects states need to be consistent with respect to their reference points.

The processing of a received CPM can be divided into four steps: temporal alignment, transformation, association and fusion. The temporal alignment step is applied to the global track list instead to the CPM data if the CPM originates from the ego-vehicle.

1) Temporal alignment: The prediction of the positions and orientations of the sender and its perceived objects is realized using a constant velocity model, see e.g. [27]. The ego-vehicles predicted position $\mathbf{r}_{e, b, i}^c$ is added to the initial global position using

$$r_{e, b, i}^c = \mathbf{r}_{e, b, i}^c + \mathbf{T}_n \cdot C_{b, c} a_{b, i}^b$$

with

$$\mathbf{T}_n = \begin{bmatrix} 0 & 1 & \frac{1}{R_E \sin^2(\psi_{i,b})} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where

$$R_N = a_{84} \cdot \frac{1 - e_{84}^2}{(1 - e_{84}^2 \sin^2(\psi_{i,b}))^2} \quad (3)$$

$$R_E = \frac{1}{a_{84} \cdot (1 - e_{84}^2 \sin^2(\psi_{i,b}))^2} \quad (4)$$

The indices - , + denote pre- and post-prediction. It is assumed that $\mathbf{T}_n \approx \mathbf{T}_n^t$, as $\Delta \Psi$ is neglectable small.

The perceived objects states are predicted in the senders body-frame. The impact of the ego-motion of the sender on the predicted objects position is compensated using

$$C_{b, c} = C_{b, c}^T - C_{b, c} a_{b, i}^b \quad (5)$$

$$r_{b, c} = r_{b, c}^c - C_{b, c} a_{b, i}^b \quad (6)$$

b) Transformation: The ego-vehicle’s current global position and orientation define the origin and orientation of the fusion-coordinatesystem (FCS). All EIS data, including the ego-vehicles is transformed to the FCS using

$$r_{b, c}^t = \mathbf{T}_n \cdot c_{b, c}^t \quad (7)$$

The PDO states are transformed to the FCS using the relative position $r_{b, c}^t$ and orientation $C_{b, c}^t$ from the transformed EIS.

$$C_{b, c}^t = C_{b, c}^t \quad (8)$$

Using the Unscented Transformation (UT) [25] in both transformation steps, the transformed state covariances have global reference.

c) Association: The x- and y-components of the position are used to calculate the Mahalanobis-Distance between every received and global track to build the validation matrix $\Omega$. If the tracks have different reference points (RP)s, e.g. front middle and rear left, the positions of both tracks are transformed to the other’s reference point via the UT using

$$r_{b, c}^t = r_{b, c}^t + C_{b, c} a_{b, i}^b$$

The leverarm is constructed from the estimated object size, dependent on the RP combination, see Tab. II. The transformed state with the smaller determinant of the position’s covariance is used for gating. In the next step a clustering
method [29] is applied on the validation matrix to split the association task into several subtasks. The modified auction algorithm [23] is applied to solve the subtasks.

d) Fusion: The state fusion step applies the Covariance Intersection [28], using the approximate variant Improved Fast Covariance Intersection described in [26].

E. Situation Analysis

The situation analysis relies on the context information, encoded in the digital map, which stores various data regarding the intersection, i.e. approach, egress and virtual (connection) lanes, traffic rules and conflict zones [36]. This map incorporates the traffic rules by lane attributes, including signs of lane priority as well as by connection possibilities (‘allowed maneuver options’) between the approach and egress lanes.

The probabilistic on-lane assignment of vehicles uses the relative pose and velocity of a vehicle to the centerline of a lane. Besides the allowed maneuver options, additional probabilistic maneuver options can arise, based on the on-lane assignment, when a vehicle is driving close to a lane marking. Reasonable forward predictions of future motion states for each vehicle are generated based on the extracted maneuver options in combination with changes of the vehicles’ dynamic motion states [37].

In this way a set of forward predicted paths for the relevant traffic lanes is generated. The relevance of a predicted path is weighted by it’s significance level (SL). The last serves as one of the situation analysis features. SL represents a probabilistic measure of plausibility for each predicted path.

To analyze the probability of a collision, pairwise vehicle-vehicle relations are established between an ego-vehicle and n perceived vehicles. Their collision plausibility in space is weighted with the corresponding significance level of predicted paths. The corresponding algorithm and models for situation interpretation and collision risk prediction have been described in [38]. For this purpose, the occupancy times of the conflict area for both vehicles are computed based on the situation features: TimeToEnter (TTE) and TimeToLeave, also known as TimeToDisappear (TTD), for the corresponding conflict area, [41], [42, p.67], Fig. 3, 4. The probability of predicted collision increases, when the probability of simultaneous occupancy of the conflict area by both vehicles increases in time. The probability of real collision is a combination of the collision plausibility in space and the probability of predicted collision.

This is performed for all recognized maneuver intentions, always pairwise to ensure the scalability of the situation analysis algorithm. Finally, TimeToBreak (TTB) is computed (see [39], [40]) in case of predicted collision, in order to derive the last possible time for warning, allowing to avoid collision by braking, Fig. 3, 4. The warning times are based on a fulfilled warning condition, which requires 70% probability of real collision and TTB ≤ 2s of the ego-vehicle (see [2] and [38]). The warning condition is still a subject of optimization, if likelihood alarms, representing the growth of collision probability are to be utilized for earlier warnings.

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TABLE II
LEVERARM CONSTRUCTION. (LEFT: RP FROM, TOP: RP TO)

Fig. 5. Prototype HMI in the MRM test-vehicle, pre (left) and post (right) wartime. The conflict partner is invisible for the driver at wartime and manually marked in the right image for clarification. The warning symbol shown does not indicate the conflict partners’ location as the driving simulator studies pointed out that this does not further improve the advisory warnings’ effectiveness, see III-B. The positions of the ego-vehicle and the conflict partner at wartime is shown in Fig. 6.
**V. EVALUATION**

First the localization requirements for the IV-IF system described in Sec. IV-D are summarized and an example for the accuracy of the fused data is given by the RMSE of one representative dataset. The evaluation and comparison of the driving simulator and the prototype system data is covered in Sec. V-B. Finally the sensitivity to false alarms in everyday-traffic is evaluated with data generated by the IPS in Sec. V-C.

### A. Inter-Vehicle Information-Fusion

The accuracy of a sender’s localization system has the greatest impact on the associability of the sender and its perceived objects to the right lanes of a digital map. The localization accuracy requirements for this task are estimated with the following equations.

\[
\begin{align*}
\delta d_{O,\text{max}} &= -\frac{1}{2}a \cdot \left(\frac{v_E}{a}\right)^2 + v_E \cdot t_B + v_O \cdot \left(t_B - \frac{v_E}{a}\right) \\
\delta r_{E,\text{max}} &= \frac{w_l}{2} \\
\delta \psi_{E,\text{max}} &= \text{atan} \left( \frac{w_l}{2d_{O,\text{max}}} \right)
\end{align*}
\]

The maximal distance \(d_{O,\text{max}}\) between target- and ego-vehicle is given by equation (11), where \(v_E\) and \(v_O\) are the ego-vehicles and conflict partners absolute speed and \(t_B\) the time to break. The maximal global position error \(\delta r_{E,\text{max}}\) is given by equation (12) where \(w_l\) is the minimal lane width. The minimal orientation error \(\delta \psi_{E,\text{max}}\) for associating an object at \(d_{O,\text{max}}\) is given by equation (13). The assumed values and requirements are summarized in Tab. III.

Received data which does not meet the requirements is rejected in the IV-IF system by a threshold, based on the equations (11), (12) and (13). The threshold is set to \(n\) times the positions and orientations standard deviations, where \(n\) defines the accepted confidence level.

The root mean square error (RMSE) of the fused conflict partners state is used to evaluate the IV-IF systems accuracy. Tab. IV summarizes the results of one representative dataset for the scenario left-turn. The ground truth is generated with RTK-GPS reference data from the ego-vehicle and the conflict partner.

### B. Comparison of driving simulator and prototype data

A warning in the driving simulator is triggered when the ego-vehicles TimeToCollision (TTT) to the conflict zone drops below a threshold of 3s, see Fig. 7. The conflict partner starts driving as the ego-vehicle passes a checkpoint, see Fig. 8. Due to the trigger rule in the simulator the warnings displayed to the test-persons are georeferenced dependent in the ego-vehicles speed. To plot the data in a comparable way, the intersection point of both vehicles trajectories is chosen as conflict point, see Fig. 6. The distance to conflict point (DTC) at TTB = 2s is 39.8m for the simulator at \(-6\frac{m}{s}\) and 43.9m at \(-6\frac{m}{s}\) for the prototype. The fact that test-persons in the simulator frequently reach higher deceleration levels due to limited force-feedback is considered by the reduced deceleration level in the prototype. The warnings from the prototype show the same pattern as those of the simulator except of five outliers, see Fig. 9, 10. The outliers triggered during the ego-vehicles braking maneuver are caused by the non valid collision probability condition due to insufficient synchronicity. The resulting mean TTB except the outliers is consistent with the maximal timing error of two times the sampling time of 0.1s, see Tab. V. The mean processing latencies to display the warning of the prototype (0.025s) and the simulator (0.01s) are neglected.

### C. Every-day traffic

The chance of getting a false alarm in every-day traffic caused by the ego-vehicles TTB threshold is analyzed with the aid of IPS data. Therefore tracks from vehicles driving towards the left turn lane stopline are extracted to simulate the ego-vehicle. To simulate a critical situation the two additional warning conditions are neglected. The results are shown in Fig. 11. The lanes stopline has a DTC of 11m. Left of the stop line, no warning should occur during common driving. The figure shows one warning in this area which is plausible as the driver has not initiated a braking maneuver at warntime. The warnings in the right area, are plausible too, as the lane to be crossed is simulated to be occupied. The assumed deceleration in TTB calculation was \(-6\frac{m}{s}\). Smaller absolute decelerations and larger TTB thresholds caused false alarms in the given setup.
VI. CONCLUSIONS

In the driving simulator studies, advisory warnings have been shown to have a great potential to reduce traffic conflicts. The warning strategy proved to be effective in the simulator and it was therefore implemented in the prototype system. Warning timings comparable to those experienced by the test-persons in the driving simulator are feasible with the prototype system in the scenario left-turn-across-path examined in this paper. An applicable parametrization to prevent false alarms was determined, too. Nevertheless the evaluation results suggest a refined modeling to deal with late warnings caused by an initial low collision probability caused by a "late" arrival of the conflict partner at the expected conflict point.

Both the warning timing and the performance of the IV-IF system depend on the accuracy of the ego-vehicles localization system. The upper bound of acceptable position errors, degrading the warning timings, has to be subject of further research.

The accuracy reached with the presented IV-IF approach relies on the explicit modeling of the road users as extended objects. Therefore precise time-stamping and accurate consistent estimates of the objects size and state in turn maneuvers are necessary for the applicability of the IV-IF approach.

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TABLE V
MEAN AND VARIANCE OF THE REALIZED WARNING TIMINGS, WITHOUT OUTLIERS ($r_w < -25m$)

Fig. 11. Situation analysis applied on real traffic perceived by the IPS
Warning drivers of approaching hazards: the importance of location cues and multi-sensory cues. [Online].

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REFERENCES


