2012 Intelligent Vehicles Symposium
Alcalá de Henares, Spain, June 3-7, 2012

Development of a general criticality criterion for the risk estimation of driving situations and its application to a maneuver-based lane change assistance system

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Abstract— **The results of a fundamental study on developing a general criticality criterion for driving situations are presented. The meaning of criticality in driving situations is defined and the influencing parameters are analyzed. Furthermore, a maneuver-based lane change assistance system is presented and evaluated in subject tests. The outcomes of the general top-down approach are compared to an evaluation criterion which is the available reaction time for the maneuver-based lane change assistance system, developed in a bottom-up approach.**

I. Introduction

Advanced Driver Assistance Systems (ADAS) are intended to reduce the number of traffic accidents as well as the harm to and loss of human lives. For active safety systems, e.g. for collision mitigation or avoidance, data from the environment sensor system is used to determine the hazard level in the specific situation. Based on this analysis, a decision regarding countermeasures, like warnings or interventions, is made. Therefore the situation assessment criterion is a crucial factor for these systems. As nowadays different ADAS functions are increasingly connected to each other, different reaction options and evolving situations need to be compared concerning their risk or criticality. Therefore it is essential that a general approach for such a criterion is developed and analyzed.

II. General criticality criterion

A. Motivation for and benefits of a general criticality criterion

There is a great heterogeneity in evaluation methods for the assessment of driving situations in general and for critical situations in particular [1]. Existing criteria are used for special scenarios such as turning, lane following, lane keeping, etc., and therefore their approach to risk estimation varies. They are designed for different purposes, using different means, such as statistics [2], the last chance of avoiding a collision by evading [3], or they are based on the presence of particular objects (e.g. pedestrians) and their distance to the subject vehicle [4].

For specific scenarios and functionalities these criteria are sufficient and have been proven in use. As the functions increasingly interact with one another, the criteria need to be capable of providing the means for assessing more complex scenarios and comparing a set of alternative actions. The simple approach of combining the criteria is not feasible in many cases, due to different reference values and a lack of comparability.

From a more abstract and general point of view, all criteria are expected to address the same problem: to quantify the level of criticality of a situation, or at least changes in this criticality. This leads to the conclusion that if the criticality level of a situation could be quantified in a general meaning, it should be possible to refer all situations to one measure. As the parameters and influence factors of driving situations vary widely, a criterion which covers all possible situations would require a high level of complexity. Therefore the most favorable approach is to set up a top-down structure for the criticality assessment of situations which allows subsequent enhancements.

Limitations due to technical boundaries are not taken into account. The criterion is developed assuming that a complete representation of the environment without the restrictions of existing environment sensor systems is available.

To be applicable for the situation assessment of ADAS, the criterion must be able to predict the development of criticality in the near future, enabling decisions about countermeasures to avoid the accident or reduce its severity.

B. Criticality

A definition of criticality applicable to this problem is indispensable. Various definitions of the term criticality can be found. In general, criticality refers to "the significance of a unit for the whole system" [5]. This includes the effects of a system´s malfunction on the system itself and its surroundings. Transferred to driving situations, the unit is represented by the subject vehicle in the traffic system, malfunctions lead to accidents and the consequences of malfunctions are harm to objects or people. To be able to describe every possible type of driving situation or accident, the criticality criterion is defined as the accident risk of a driving situation. Here risk is used according to the meaning

Manuscript received January 15, 2012.
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978-1-4673-2118-1/$31.00 ©2012 IEEE

of ISO 31000 [6] and is described by the probability of occurrence of a harmful event combined with the amount of damage caused by the event. Using this definition, accidents with collisions are covered as well as off roadway accidents and rollover situations on or off the roadway.

By measuring the amount of damage and harm caused by an accident, the criticality criterion is able to provide the means to evaluate situations according to their threat to the participants. A situation of an unavoidable accident causing negligible damage is assessed with a lower value than a situation in which an accident is unavoidable as well, but results in more severe damage.

C. General criticality assessment

The possibility of an accident is supposed to be related to the amount of space available for reaction. Existing approaches evaluating driving situations in a more general way use this premise, calculating the possible motions of the system vehicle and other surrounding vehicles. A probability for a collision is calculated using the areas the objects cover and the amount of overlap depending on the calculation time steps [7]. This approach is used as a basis and is extended to achieve a general criticality assessment in the following.

To assess the criticality of a driving situation, the objective situational risk of an accident must be calculated. Therefore the positions of potential hazards in the surroundings need to be identified. Starting from the initial situation the following steps are conducted.

First, the expected trajectory of the subject vehicle in the near future is calculated based on a modified model of constant accelerations. This model assumes constant accelerations of the vehicle in longitudinal and lateral direction. The acceleration in lateral direction is used to calculate a yaw rate, using a linear one-track model. The assumption of a constant lateral acceleration is determined by the near future course of the road. This modification is needed to depict maneuvers such as lane changing, entering and ending curves, turning, etc.

In the next step, objects in the surroundings of the subject vehicle are classified. With the knowledge of the object type and motion state, a motion prediction model is selected for every object and the expected object trajectory is calculated. With this information, irrelevant objects whose trajectories do not result in conflicts or collisions are removed from further analysis. In the following, the possible locations for the subject vehicle are calculated depending on prediction time steps. Additionally, areas where the crash is unavoidable if the vehicle (respectively the driver or system) does not react at all are identified. These are determined by objects in the present course of the vehicle and are calculated from the collision object backwards. Assuming a constant acceleration potential in lateral and longitudinal direction, the possible locations of the subject vehicle are represented by circles growing with increasing prediction time, as shown in figure 1.

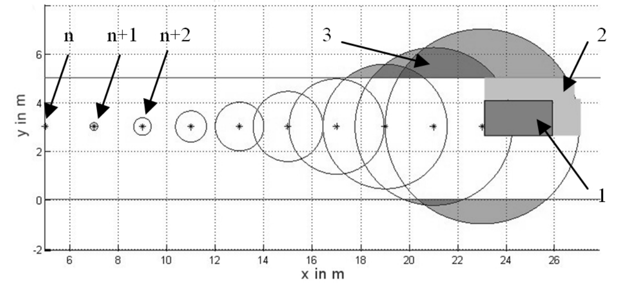

Figure 1: Possible locations of the subject vehicle; with n = possible location of the subject vehicle at the current time step, 1 = object, 2 = blocked area, 3 = off roadway area

With the known object positions at each time step, the area occupied by other objects, including the areas whose access is blocked, is calculated. The percentage of this area $A_{collision}$ in relation to the area of the entire circle A_{circle} in this time step is the location quotient $L_{collision}$ of the situation, which is closely related to the collision probability.

$$L_{collision} = A_{collision} / A_{circle} \quad (1)$$

With knowledge of the course of the roadway, the area of the circle is divided into parts off and on the roadway. The location quotient $L_{off\ roadway}$ for leaving the road is calculated analog to $L_{collision}$.

In addition to the accident probabilities, the severity of the accident types “Collision” and ”Getting Off the Road” must be calculated. The severity of an accident is influenced by many different factors and parameters. Here, the severity is described using an impact factor I as a simplifying approximation.

The a priori estimation of the accident severity strongly depends on driver behavior during the prediction time. Dependent on the actions performed by the driver, the estimated collision speed and the degree of overlap, the damage and harm of an accident changes. For calculating the objective criticality, one possibility of the crash severity must be chosen. This is done by selecting the situation with the lowest damage and harm for all participants. Nonetheless, depending on the purpose of the particular analysis, other choices may be made. This best-case scenario is used for estimating the accident risk for both accident types. Thus the collision risk is

$$R_{collision} = L_{collision} \cdot I_{collision} \quad (2)$$

With this information, the criticality of the situation can be calculated as the accident risk of a driving situation, consisting of the sum of the collision risk and the risk of an off roadway accident.

$$R_{total} = R_{collision} + R_{off\ roadway} \quad (3)$$

To identify the feasibility of this method, it is compared to a risk assessment method designed for specific scenarios as described in Section A. This is done for a maneuver-based lane change assistance system.

III. MANEUVER-BASED LANE CHANGE ASSISTANCE

A. Introduction

According to an analysis [8] of the German In-Depth Accident Study (GIDAS) of 2003, 7 % of all fatalities on the German Autobahn were lane changing accidents and about 13 % of all accidents with injured people in 2010 were collisions with a vehicle driving in an adjacent lane [9]. Lane changing is a very demanding maneuver [10] because the driver must control the longitudinal and lateral dynamics and check for vehicles in several lanes in parallel [11, 12]. Velocities and distances of other vehicles are often estimated inaccurately or vehicles are not even noticed [13, 14]. In agreement with the great mental and physical burden exacted by this maneuver, drivers show a demand for assistance during lane changes in interviews [15].

Therefore, manufacturers offer Lane Change Decision Assistance Systems (LCDAS). These systems inform the driver of vehicles in the blind spot area (and, depending on the manufacturer, of fast- approaching vehicles), and in addition warn in case of dangerous lane changes using optical symbols in the outer mirror, acoustic warning devices or steering wheel vibrations. However, this information addresses perception but does not offer the driver the ability to adapt his or her driving style to the adjacent vehicles by assisting in cognition.

Therefore, a maneuver-based lane change assistance system is developed focusing on the driver's need for information and offering assistance on the perception and cognition level by recommending lane changes and a certain driving behavior to reduce the workload without automatization of driving. Safety and comfort should also be optimized.

B. Specification

In the past year enormous progress was made in developing fully autonomous vehicles. This was shown in competitions like the DARPA Urban Challenge [16], by the fully autonomous drive of an Audi TTS quattro on partly loose ground up to Pike's Peak, and by projects like Braunschweiger Stadtpilot, Google Self Driving Car and Italian VIAC. Fully autonomous vehicles take over all three levels of a simple driver model describing human information processing as a sequence of perception, cognition and action [17]. Partly autonomous systems, e.g. Conduct-by-Wire (CbW) [18], assist the driver on all three levels. Finally, as shown in figure 2, a LCDAS assists the driver only on the perception level. The LCDAS does not supply information like how to synchronize with the target lane, when a lane change is possible and which adjacent gap is the best one. The maneuver-based lane change assistance system assists on the perception as well as on the cognition level.

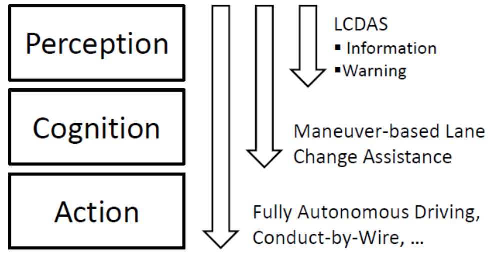

Figure 2: Simple Driver Model

Driver and vehicle communicate on the guidance level using a so-called maneuver recommendation, which consists of advice about driving behavior for a safe lane change. It includes *the beginning and the ending of the lane change phase*, *the minimal change of acceleration/ deceleration needed* and *the lane change direction*. Thereby, the demanding cognitive task of checking the feasibility of lane changing, the selection of an adequate gap predicting the driving situation, as well as taking other influences such as acceleration performance and benefit estimation into account, are dispensable.

The maneuver-based lane change assistance is defined as a single-task combining assistance, communicating with the driver on the guidance level via maneuver recommendation.

C. System Functionality

The presentation of the maneuver recommendation is based on four pre-defined open loop control programs: no lane change, lane change with acceleration, lane change with deceleration and lane change with constant velocity. These programs are presented to the driver via a 5.4” display mounted on top of the dashboard. Figure 3 shows the visualization of the maneuver recommendation.

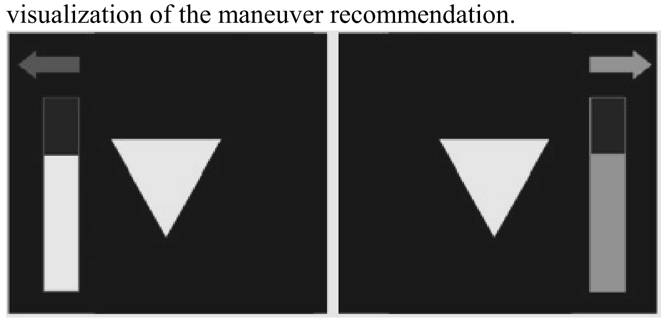
Figure 3: Visualization of the Maneuver Recommendation

On the left- hand side of this figure, the lane change is not possible. Therefore, the frame of the time bar on the left and the arrow showing the lane change direction are colored red. The filling status of the time bar, showing the timing information, and the triangle in the middle of the visualization, which symbolizes the acceleration, are colored white.

The system architecture as well as the main system modules are described in [19].

D. Test Design

For safety reasons, the tests are run on a test track. According to the number of occurrences and accidents [8], the test scenario is a lane change to the left motivated by a slow vehicle driving ahead. In one instance the leading vehicle drives at constant speed, and in the other it decelerates to increase the workload. The test subject and the leading vehicle are passed by three adjacent vehicles. Therefore, the test subject must choose from four alternative gaps. The combination of two scenarios, three system variations consisting of *driving without a system, driving with LCDAS* and driving *with the maneuver-based lane change assistance system (MLCAS)*, in addition to two workload measurement methods, leads to a total of twelve rounds of driving.

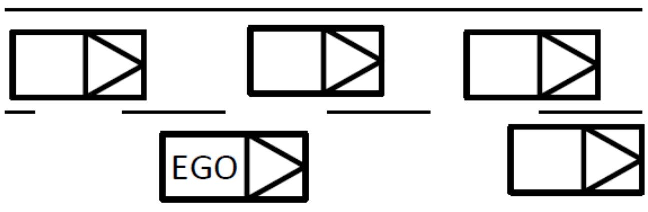

Figure 4: Scenario Setup

E. *Test Subjects*

For evaluating the assistance system 37 test drivers participated in the tests. They are approximately, uniformly distributed in three categories - sex, age and annual driving mileage.

IV. System Evaluation

A. *System Evaluation*

Three vehicles are taken into account for the evaluation of a lane change: the leading vehicles on the start as well as on the adjacent lane and the vehicle limiting the gap backwards on the adjacent lane. For evaluating the maneuver-based lane change assistance system, a criterion for comparisons among the three system variations is needed.

1) *Criterion*

Widely used criteria for describing two vehicles following each other are the time-to-collision *TTC*, the headway time τ and the deceleration for avoiding a collision D_{req}. D_{req} and *TTC* are congruent. The ability to describe the criticality depends on the situation. Therefore, [20] and [21] conclude that neither *TTC* nor τ describe the criticality of the situation adequately. So far, no interpretable and easily understandable combination of the criterion is known.

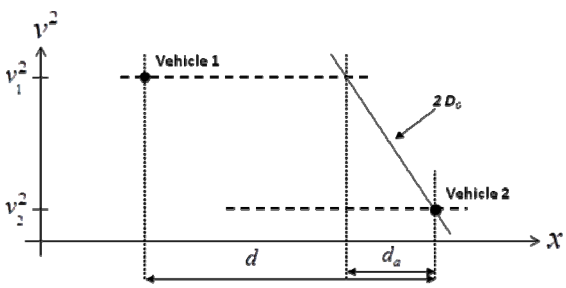

Figure 5: Two Vehicles Following Each Other

Figure 5 shows a leading vehicle 2 and a faster, following vehicle 1. The velocity is plotted squared over the corresponding distances; the deceleration then can be calculated by the derivation. Assuming the maximum deceleration is known, the distances and the velocities are measured and the minimal braking distance can be calculated using the equation

$$d_a = v_{rel}^2 / \left(2D_0\right). \tag{4}$$

The distance left for a reaction is

$$d_{react} = d - d_a. \tag{5}$$

Assuming, that at the position of the leading vehicle, the following vehicle has the same velocity as the leading had at that point, the following vehicle is able to copy the acceleration of the leading vehicle. The available reaction time is calculated under the assumption of zero acceleration using the following equation:

$$\tau_{react} = \left(d - d_a\right) / v_1 = \left(d - v_{rel}^2 / 2D_0\right) / v_1 \tag{6}$$

2) *Results*

The results are presented in figures 6 to 8, separated for each of the vehicles included, showing the cumulated percentage of the available reaction time. The higher the reaction times, the further right the curve and the safer the situation is.

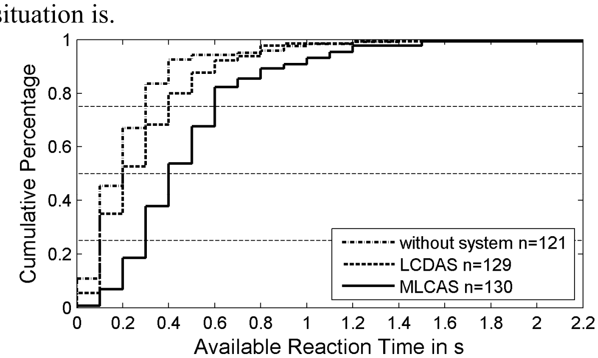

Figure 6: Leading Vehicle on Target Lane

In all figures, the LCDAS shows higher available reaction times than the driving without a system, while MLCAS shows even higher values than LCDAS.

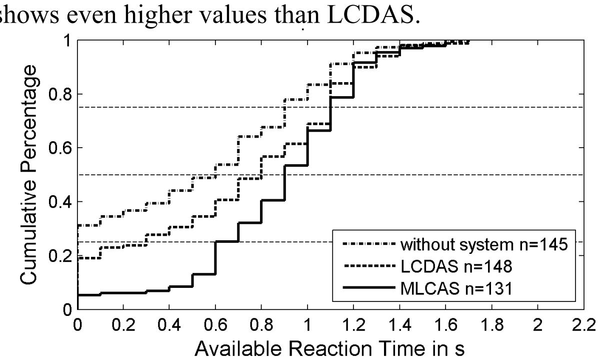

Figure 7: Following Vehicle on Target Lane

The Wilcoxon rank-sum test shows significantly higher reaction times for driving with MLCAS compared to LCDAS and for LCDAS compared to driving without any system. Therefore, an increase in safety is shown for driving with a maneuver-based lane change assistance system.

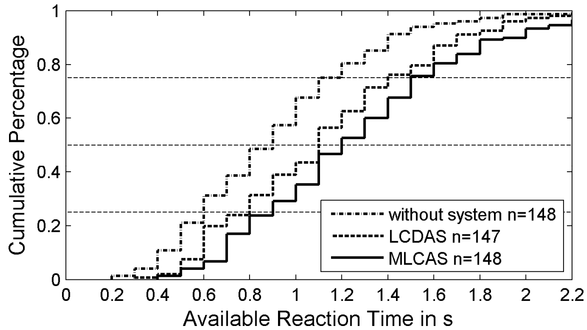

Figure 8: Leading Vehicle on Start Lane

B. Exemplary application of the general criterion on lane changing maneuvers

To give an example of the results of the general criticality criterion in comparison to results of a specific system evaluation, the general criterion is applied to the lane change situation. The initial scenario is set analog to the scenario used for the specific evaluation. According to the design of the general criterion, the situation assessment is done as follows: The trajectories of the system vehicle and the other vehicles are predicted, using the modified model of constant accelerations. After the object classification, relevant remaining objects are the leading vehicle, the three vehicles on the adjacent lane and the crash barriers on the side, shown in figure 9.

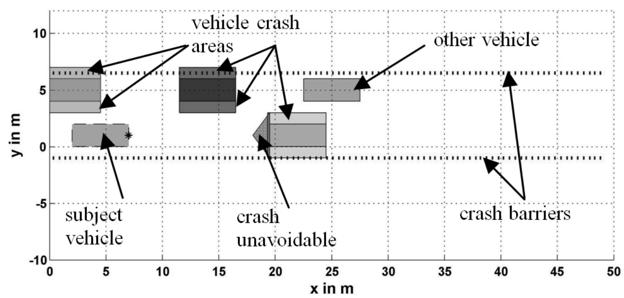

Figure 9: Representation of the initial scenario

In the interests of clarity, the subject vehicle shown in figure 9 is only displayed in the initial position and reduced to a point mass in further prediction steps. Considering the size of the subject vehicle, the potential collision objects are extended with a vehicle crash area, where a collision already occurs because of the subject vehicle´s dimensions.

Based on its acceleration potential, the possible locations of the subject vehicle are calculated, depending on the driver input. The overlap of the surface area, used for the computation of the accident probability, is shown in figure 10 and 11, where different time steps of the prediction are plotted. In this scenario, "Getting Off the Road" accidents are not possible, because of the limiting crash barriers. Figure 10 shows the last time step when a lane change without imminent collision is still possible.

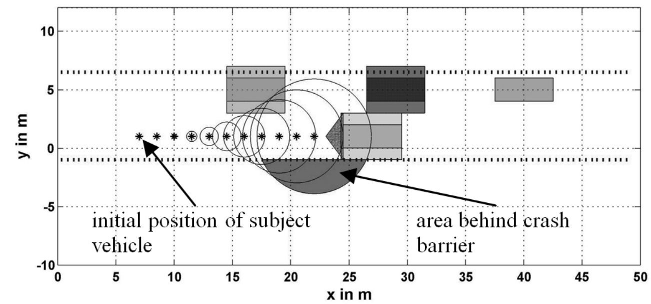

Figure 10: Predicted Situation Development with n = 10 Steps

Additional prediction steps of the situation development are shown in figure 11. Here, an increased probability of collision is a result of the collision probability with either a crash barrier or one of the other cars. A lane change maneuver is not possible because of the insufficient space for passing the gap between the two vehicles.

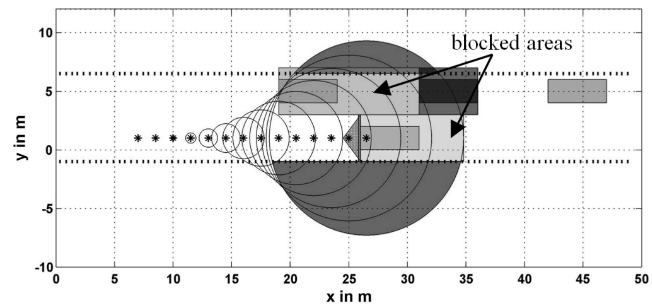

Figure 11: Further Situation Development with n = 13 Steps

The resulting development of the situations location quotient is shown in figure 12.

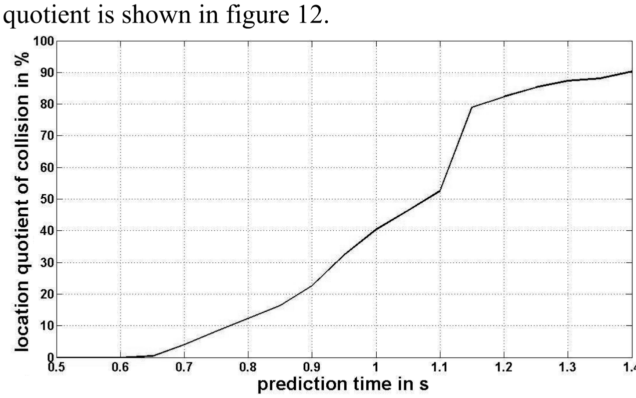

Figure 12: Development of the Location Quotient

In the chosen scenario there is at least one possibility of avoiding an accident by decelerating. Using the best-case scenario as described above, the intention of accident avoidance is assumed; for that reason this case, which lacks damage or harm to an involved object or person, is selected for calculating the accident risk.

The resulting accident probability, the decision if an accident is avoidable and the accident severity depend strongly on the chosen setting of the scenario. Also in this example the risk estimation is limited to the subject vehicle. Nevertheless it is also applicable for the other involved vehicles.

C. Comparison of time-to-react and general criterion

The approach of calculating the time-to-react for the involved vehicles uses the available time for avoidance. It considers only two objects and their longitudinal reaction potential at one characteristic point in the situation. Influences on the risk by limited available roadway, e.g. due to crash barriers, cannot be taken into account.

The general criterion enhances the timely risk estimation by a spatial approach. The time-to-react is implicitly included by the area where a collision is unavoidable without driver reaction. In addition it considers multiple objects and their positions and possible longitudinal and lateral reaction. Thereby it allows a more holistic assessment, which is able to compare the criticality of different situations. On the other hand, due to the predicting character of the criterion, it is more prone to changes in the objects´ behavior, resulting in changes of the trajectories. The longer the prediction time, the more inaccurate the risk estimation becomes.

V. Conclusion & Outlook

To achieve a comparability of the assessment of situations for different scenarios, a general criticality criterion is needed. The approach developed here is evaluating the risk of an accident a priori by assessing the criticality of the situation by the probability of positions.

The applicability on a lane change maneuver has been shown in general and in contrast to a specific evaluation method for lane change maneuvers. The approach can be considered as starting point which needs refinement and further validation. The determination of concrete values of criticality has been made based on simplifications and assumptions that need to be investigated and detailed. The object motion prediction used here is very simple and thereby not feasible for a direct application in ADAS functions. To compare the developed approach to a specific evaluation method it is sufficient to use similar object motion prediction hypotheses in both processes.

However, as for all predictive algorithms, the hypotheses of human behavior and interactions of objects guided by humans are highly determining for the quality of the prediction and the valid prediction time. Further research in this area is needed to determine the requirements for a suitable enhancement addressing this problem and to quantify the suitable prediction time.

If it can be proven in further analysis that the approach discussed here is capable of assessing different scenarios with the same process, the approach can be developed for a broader field of use. In the future, the general criterion has to be applied and verified in different scenarios and tests in comparison to other criteria to analyze its capability in practice.

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