

Situation Awareness Assessment in Critical Driving Situations at Intersections by Task and Human Error Analysis

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Abstract

The rapid development of sensor and tracking technology enables deployment of new advanced driver assistance systems (ADAS) that support the driver not just on highways but in urban areas as well. Intersections particularly present very critical traffic scenarios where almost 35% of accidents occur, partially due to the present lack of in-depth research about human errors and their determinants. The first step in ergonomic design of ADAS is to identify the specific situations in which drivers require support.

To contribute to identification of such spots, situation awareness of 20 drivers in four critical intersection scenarios was explored. The study was conducted in the static-based driving simulator. The applied approach consisted of assessing drivers' expectations and mental workload and of comparing of theoretically correct cognitive behavior to experimentally collected data. Thereupon, intersection scenarios were divided into five segments and for each segment a task analysis was made.

The study has shown that the driving simulator environment can be successfully deployed to provoke and explore various driver errors. The results have revealed that in scenarios when information is objectively missing, majority of errors happened because the drivers had inaccurate mental models of particular scenarios. To the contrary, in the complex scenario the major cause of accident was information overload. Furthermore, the task analysis disclosed applicable areas of intersection assistance.

1 Introduction

Introduction of a new sensor and tracking technologies together with communication protocols like Car2Infrastructure or Car2Car will enable assistance support in urban areas. Appropriate design of Human-Machine Interface (HMI) is crucial for effectiveness and acceptance of such assistances. This is unachievable without understanding the origins of accidents. As human error accounts for about 90% of them (Gruendl, 2005), investigation regarding the causes of these errors is of essential importance.

It is the cause of an error which should be directly addressed by ADAS. For this purpose, standard accident analysis cannot provide sufficient information. Accident analyses reconstruct the chain of events leading to an accident but do not reveal the cognitive processes causing the driver's error. For instance, the same accident type can be caused by a different error. Therefore, they present a 'post-hoc' reasoning process, very often lacking all information and can only partially lead to a better understanding of human performance issues.

Scientific investigation of the causes of errors leading to accidents raises a number of methodological issues. Accidents are rare occasions and in order to systematically analyze errors leading to them, either a practically unfeasibly profuse experiment which will collect a huge amount of driving data should be conducted or the drivers would have to be exposed to critical scenarios which will provoke errors. Both approaches are accompanied with several methodological problems. For an accident to happen an average driver would need to travel 62 million miles (Nowakowski, 2006). For the near-accidents, the mileage is much less, but systematic analysis is hard to conduct. The second approach require a creation of appropriate scenarios provoking particular error. Hereby, several problems emerge: how to expose drivers to critical scenarios, how to choose appropriate generic scenarios to systematically provoke driver errors and how to desing such an experiment. Exposing participants to a real-life experiment with critical conditions cannot be done. Also, up to recently, the conduction of such studies in driving simulators was ineffectual as prevailing simulation software were not mature enough to simulate such a conditions. With a new generation of software critical urban scenarios can be created.

This paper presents four critical scenarios designed to cause different type of driver error and an analysis of drivers' situation awareness in these scenarios in order to identify driver strategies and the most common errors. Background information about the chosen approach, suggested generic critical scenarios and study procedure are firstly presented, followed by the most important results and observations.

2 Theoretical Background

There are various different definitions of a human error in the literature. Nonetheless, held in common amongst all of them is that the error is inseparable from the intent of achieving a desired goal. In order to develop intentionality, a human has to be aware of the situation and to pay attention to it. Therefore, in order to analyze the circumstances in which an error has occurred, a full understanding of the situation is necessary. This can be described with the concept of *Situation awareness* which lies at the heart of all human decision making and performance (Endsley, 1999). In this chapter a connection between driver error and accidents is described, followed by explanation of situation awareness and task analysis procedure used to assess it. By determining omitted tasks and analyzing driver expectations and scenario comprehension, a better understanding of driver inner models can be gained and segments with higher error probability can be identified.

2.1 Accidents Origin and Driver Error

Human error, solely, does not have to lead to an accident if other factors do not contribute. Therefore, analysis of near accidents is as relevant to understanding causes of accidents as accident analysis itself. By analyzing human behavior we can observe errors which did not lead to an accident but could have if other factors would have been present. From time to time every driver commits an error, but they do not necessarily lead to an accident as they get compensated by the drivers' reactions or reactions of the other road users. Traffic scenarios leading to an accident are often very complex and are a combination of several factors. From a system-ergonomic point of view an accident (top-event) can arise if a traffic conflict and an inappropriate treatment of the conflict occur ((Bubb, 2005), see Figure 1). The traffic-conflict can be defined as a traffic situation in which traffic participants challenge a risk of causing a collision if they do not change their direction or speed. Thus, just an unresolved conflict leads to an accident.

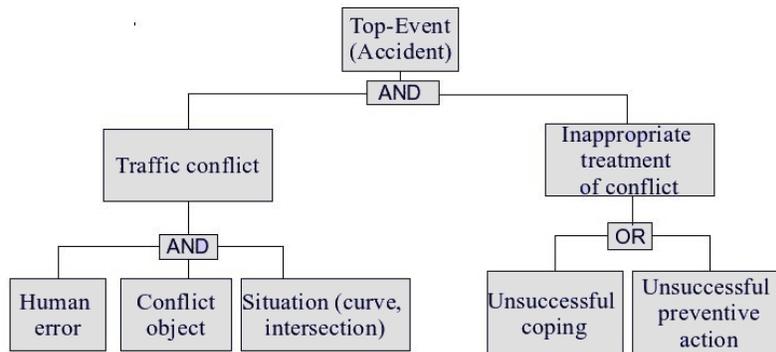


Figure 1: Accident tree, adopted from (Reichart, 2000). Human error is necessary but not a sufficient condition for accident occurrence

Human error can be either random or systematical (Whittingham, 2004). Accidents caused by random errors can be just simple situations, but in these situations a peak mental overload or a usage of the wrong inner model can cause driver failure. Errors causing such accidents are unpredictable. Fortunately, they are very rare. Most human errors have underlying systematic causes that can be identified, studied and at least partly addressed in order to make the errors less likely (Whittingham, 2004). By understanding the strategies and inner models the drivers use, some knowledge of when they could appear can be gained. In order to design ergonomic HMI, it is not enough just to find out which error happened but to understand why human assessment and actions made sense to them at the time.

As already argued, in order to analyze driving strategies leading to an error, the driver has to be exposed to a scenarios provoking the error. For a systematical analysis, an appropriate error classification is necessary. Many different classifications have been developed over the years. Gruendl (2005) evaluated Hacker's model as the best choice to analyze driver errors because of its inner logic and theoretical background. Therefore, for the purpose of this study Hacker's model was further adopted for intersection scenarios:

- **Information 'objectively missing'**

- * view occlusion (*other vehicles, vegetation, infrastructure, curve...*)
- * visibility conditions (*darkness, rain, snow, fog, lights from other vehicles...*)
- * others (*missing traffic sign...*)

- **Information 'not objectively missing'**

- * deficient usage of information:
 - information overlooked (*inside, outside distraction, look-but-not-see, wrong focus, overload...*)
 - information forgotten (*processing deficits (7±2 chunks), low concentration...*)
 - conscious violation (*excessing speed, not keeping distance, not respecting traffic signs, right of way...*)
- * wrong usage of information:
 - wrong evaluation (*of distance, speed, intention of other traffic participants...*)
 - wrong action or goal (*giving gas instead of braking...*)
 - wrong action (*too strong steering...*)
 - operation mistake (*confusing gas and brake pedal...*)

2.2 Situation Awareness

To analyze the underlying cause of driver errors, their driving strategies have to be understood. To understand the driving strategies means to understand the parameters of the selection process of a specific inner model for a particular driving situation and to understand the way these models are built. This process can be described with the concept of situation awareness. Analyzing situation awareness in critical scenarios in which *information is objectively missing* is particularly of interest to this study.

Situation awareness is a term derived originally from the aviation field and it aims to describe and integrate all different cognitive aspects necessary for the correct performance of some task. Endsley (1995) defined situation awareness as 'the perception of the elements in the environment within a span of time and space, the comprehension of their meaning and the projection of their status in near future'. Situation awareness starts with perception of elements in the current situation. Correct perception and comprehension are critical for proper decision-making.

Figure 2 presents a system-ergonomic model of information processing (Bubb, 1993). Storage of information is happening in a several steps. When exposed to some stimulus, information content is first saved in so called *sensory memory*. From sensory memory information can be further moved to a *short-term memory* which has limited capacity. In contrast to short-term or a *long-term memory* has unlimited capacity. It contains different inner models of a certain situation. Each model consists of two parts: perception-action and action-perception parts, which correspond to deducing an action based on a perception of the situation and the mental representation of the consequences of the performed action, respectively. The decision making mechanism, which complies to the capacity of the short-term memory is choosing the most appropriate inner models for the current situation. The line between conscious and subconscious on Figure 2 points out that the selection of an inner model and comparison with sensory memory happens subconsciously. Just the result of the action which deviates from the mental representation is perceived consciously. Therefore, accurate mental models are one of the prerequisites for achieving situation awareness.

2.3 Task Analysis

One of the methods for assessing situation awareness and determining the location and causes of errors is a task analysis. The task analysis approach used in this study consists of comparing of theoretically ideal cognitive behavior to experimentally collected data. The ideal behavior is deduced from the task analysis methods proposed by: (Hannigan, 1998), (Richard et al., 2006) and (Fastenmeier and Gstalter, 2007) and adopted after the discussion with a driver instructor. According to these proposals, each intersection was divided into five segments: *Approach, Deceleration, Intersection entry, Prepare for, and Execute turn*. An example of how the situation was divided into segments and how the tasks were assigned are given for Scenario 1 in Figures 3 and 4, respectively.

Special attention is dedicated to the visual tasks. Based on the definition given in (Schweigert, 2003) each visual task is classified into one of the four priority classes. Tasks belonging to the first category are of essential importance and their omission would lead to a very high accident risk. The second category is comprised of slightly less important tasks; these are taking into account erroneous behavior of the other traffic participants and their

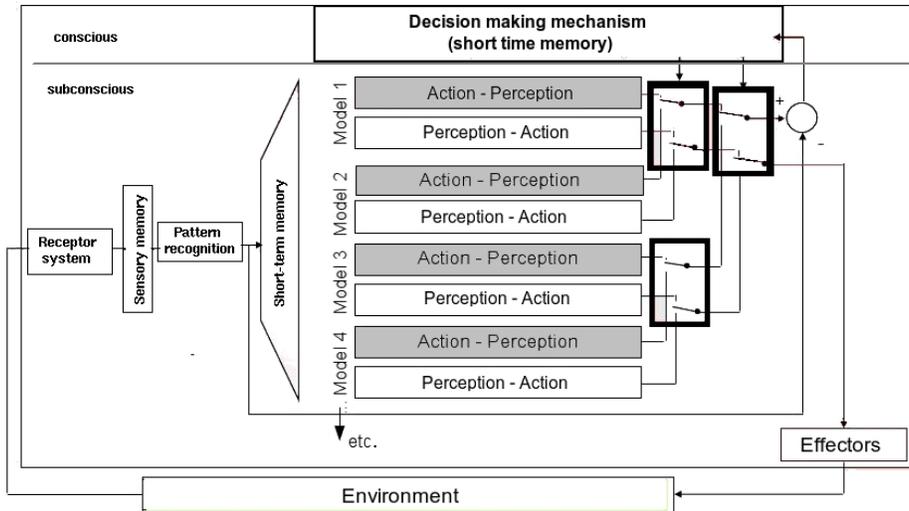


Figure 2: System ergonomic model of information processing (Bubb, 1993)

. Decision-making mechanism chooses the most appropriate inner model for the current situation

omission can lead to an accident in such cases when the other drivers do not adhere to the traffic rules. The third category comprise of tasks necessary for vigilant behavior and include long-term planned tasks like observation of the traffic participants ahead (in the distance). Finally, all the tasks having nothing to do with the driving itself, such as the interior observation of the vehicle belong to the fourth category. A clear distinction between the tasks in the first three categories still remains difficult.

With an eye-tracking system just foveally received information can be tracked. However, drivers are getting a significant amount of information from the peripheral area and it is important to distinguish between tasks which can be performed foveally or peripherally. This depends a lot on experience as shown by Underwood et al. (2003). Even though, it is generally disputed which vision is more important for different driving tasks, it is certain that in situations under a high time strain such as intersections, foveal vision is the main source of information (Schweigert, 2003). Therefore, attached to each task is a noted assignment of whether the task can be foveally or peripherally performed, adopted from Miura (1986). He has characterized different situations with regard to the importance of peripheral and foveal vision.

The order of the task is irrelevant for untimely critical segments such as *Approach* and *Deceleration*. As far as our scenarios are concerned, the order of visual tasks in *Prepare for* and *Execute turn* is important and special attention was given to it.

3 Experiment - Goal and the Method

In order to be able to analyze erroneous driver behavior at all, first issue to be clarified is whether and what kind of driver errors can be systematically provoked in an experimental environment. To evaluate that possibility, four critical scenarios were designed based on the Hacker error classification. First distinction is among errors when *information is objectively missing* and errors when *information is not objectively missing*. Scenarios were designed in a manner to provoke both types of errors. Situation awareness is analyzed by exploring key factors: anticipation, attention, perception, expectations and risk (Endsley, 1999).

In three scenarios, the driver has obstructed view (object occlusion causes almost 50% of intersection accidents (Hoppe et al., 2007)). In **Scenario 1**, the hazardous object is visible when approaching the intersection but visually concealed in the critical moment; in **Scenario 2**, the hazardous object is concealed all the time and driver's attention is 'guided' towards another object; in **Scenario 3**, the hazardous object appears in the very last moment and was not previously visible due to sight obstruction. In that way drivers' expectations and mental representations of possible hazards which are objectively missing can be investigated.

In an experimental environment, creating conditions to cause an error when information is objectively missing is rather simple. More problematic is to provoke an error when information is not objectively missing, as conditions

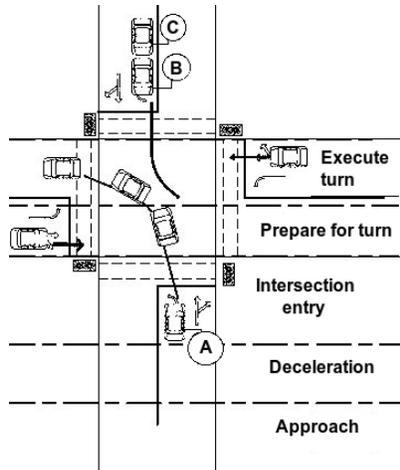


Figure 3: Example of dividing the intersection scenario into spatial segments: *Approach*, *Deceleration*, *Intersection entry*, *Prepare for*, and *Execute turn*. By tasks analysis in each of these segments, different aspects of situation awareness can be assessed and the most common errors identified

for such errors cannot be easily reproduced. The purpose of **Scenario 4** is to investigate whether such an error can be generated in experimental conditions.. Therefore, a scenario with a high information density is created and it is analyzed what kind of driving tasks are omitted due to information overload i.e. whether driver have enough resources to anticipate the full situation.

The goal was to design the scenarios in a way, that any serious error leads to an accident and to evaluate whether such situations are perceived as realistic. The main problem was how to design them in order that they are critical for both defensive and sporty drivers.

Experimental Environment and Implementation of Scenarios

The study was conducted in the fixed-base driving simulator at the Institute of Ergonomics at Technische Universität München (see Figure 5(a)). The simulator vehicle is BMW 6 series and it consists of 3 projection walls with 180° fields of view. The simulator has a realistic vehicle dynamics, 6 channel sound and a possibility to record all vehicle dynamics.

Simulation software used for driving simulator provides flexible framework for implementations of different scenarios and for controlling other vehicles and pedestrians as well as the look and feel of the environment (SILAB). Due to its modularity, it is open for extensions by writing customized components. Furthermore, all data are accessible both during the simulation and for offline evaluation.

Intersection scenarios are designed in a dedicated graphic editor. The design consists of laying out the geographical structure of the scenarios, roads, lanes and environments. The most complicated part is the synchronization of the traffic. This is done by placing so called flowpoints on the road. They allow direct control of the other vehicles. Flowpoints are placed as markers on the lane and are activated by driving over them. Synchronizing the traffic in a way that critical situation is activated for both defensive and sporty drivers took some time for trial and error and it appeared to be the biggest problem when implementing the scenarios.

Eye-tracking system used for this study was Dikablis (digital wireless gaze tracking system). Dikablis is light-weight head-mounted eye tracking system developed at the Institute of Ergonomics, TUM (see Figure 5(b), (Lange et al., 2005)). It consists of two cameras: one recording the eye and the other one recording the field of view. With an available graphical user interface, the system can be calibrated and the data can be analyzed both manually and automatically.

Experimental Course

The experimental course consisted of two urban environments (cities) and rural roads connecting them. In each of the two cities, there were around ten intersections whereby four of them represented critical situations.

TASKS	VISUAL TASKS	TASKS	VISUAL TASKS
	(1) Approach		(2) Deceleration
<ul style="list-style-type: none"> - recognize intersection - evaluate distance - decelerate - keep the lane - recognize intersection type (right of way, traffic lights and signs, number of lanes) - prepare for lane change - set the blinker 	<ul style="list-style-type: none"> - look ahead, I - scan for hazards, II, III - check oncoming traffic (F), III - visually evaluate distance (crosswalk), II,III - focus traffic lights (F), I and drive path, III - check for lights changes, I - check for other traffic signs (PP), III - secure lane change (F), I, II - irrelevant visual tasks, IV 	<ul style="list-style-type: none"> - prepare for braking - change lane - braking - keep the lane - evaluate braking distance 	<ul style="list-style-type: none"> - observe drive path, II - scan for hazards, III - evaluate braking distance, I - check for following vehicles, (F), II - observe if traffic lights are changing, I - irrelevant visual tasks, IV
	(3) Intersection entry		(4) Prepare for turn
<ul style="list-style-type: none"> - stop at the crosswalk - drive off due time after lights change - scan for bicycles and pedestrians - scan for hazard-vehicles from right and left 	<ul style="list-style-type: none"> - check for traffic lights change, I - scan environment for hazards, II - check for followers, (F), III - check for pedestrians and bicycles from right, (F), I - check for pedestrians and bicycles from left, (F), I - check oncoming traffic, (F), II - check for vehicles without right of way - left - visually scan driving path, III - irrelevant visual tasks, IV 	<ul style="list-style-type: none"> - stop at the middle of intersection to ensure yielding a way to oncoming traffic - choose appropriate time gap 	<ul style="list-style-type: none"> - check for vehicles coming from left, (F), II - monitor oncoming traffic, (F), I - check behind the truck (F), I - observe drive path - irrelevant visual tasks, IV
	(5) Execute turn		
<ul style="list-style-type: none"> - observe drive path - steer and accelerate to initiate the turn - keep the lane 	<ul style="list-style-type: none"> - check for pedestrians and bicycles from right, (F), I - check for pedestrians and bicycles from left, (F), I - scan the area, III - monitor oncoming traffic, (F), I - observe driving path (F), I - irrelevant visual tasks, IV 		

Figure 4: An exemplary task assignment to each of five spatial segments for Scenario 1. Each visual task is characterized by priority level and whether the task has to be performed foveally (F) or peripherally

Scenario 1 is a left-turn scenario at a signaled intersection where simultaneously turning vehicles in the opposite left-turn lane block the drivers' view. It represents a situation with a physically occluded hazardous object (see Figure 6). The driven vehicle is approaching intersection and is assigned the task to turn left. During the *Approach* intersection segment, traffic lights are set red. Oncoming traffic (vehicle B) is programmed to turn left as well. Behind vehicle B, there is a hazardous vehicle (vehicle C) programmed to continue straight through the intersection. Vehicle C is visible when approaching the intersection but not while waiting for the green light. To increase the possibility of the loss of information, the duration of the red light phase is set to 10 seconds.

Scenario 2 is a right turn scenario at a signaled intersection with a leading truck vehicle (see vehicle B at Figure 7(a)) obstructing part of the view. It represents a situation with a physically occluded hazardous object (Pedestrian PA at Figure 7(a)) whilst the driver's attention is supposed to be caught and led by another object. The driven vehicle is approaching the intersection and is assigned the task to turn right. The leading truck vehicle is already waiting for the green light and has the right blinker set. After the traffic lights change to green, the truck slowly begins turning, passing a pedestrian (PA), who is crossing from the right to the left side of the street. This pedestrian is visible to the driver. After the pedestrian (PA) passed the street, the truck drives further and the hazardous pedestrian (PB) who was not visible to the driver appears and crosses from left to the right.

Scenario 3 is a left turn scenario at a T-junction giving way to the right. It represents a situation with a physically occluded hazardous object which is coming very unexpectedly (see Figure 8). When the driven vehicle approaches the intersection, vehicle B appears from the left side and has to yield to the driven vehicle. The view on the right side is occluded by parked vehicles. When own vehicle reach an intersection, a hazardous vehicle C appears from the right side and drives straight through the intersection.



Figure 5: Experimental setup used for the pilot study: (a) Static-based driving simulator of the Institute of Ergonomics, TUM (b) Eye tracking system: Dikablis (digital wireless gaze tracking system)

Scenario 4 is a left-turn scenario at a four lane signaled intersection, It represents a very complex scenario with regard to the number of objects in the visual scene pertaining to as well as the driving maneuvers required. Such intersections are usually regulated by traffic lights, but to increase complexity they are set to be out of order. When approaching the intersection the driver has to yield to the right of way of crossing traffic. Crossing traffic is coming from both the left and right sides. Firstly, traffic coming from the left is leaving the intersection (see Figure 9(a)). Shortly afterwards traffic comes from the right (see Figure 9(b)). When the driven vehicle enters the intersection, hazardous vehicle B is approaching from the right. At the same time another hazardous vehicle (vehicle C) is approaching from the front. When the driven vehicle leaves the intersection, a hazardous pedestrian (PA) is activated to cross from right to the left side of the street.

Procedure and Test Sample

After getting a brief introduction to the study, participants drove a practice course to get familiarized with the simulation environment. Participants were instructed to drive as they would normally drive and to obey traffic regulations. Subsequently, they drove the experimental trial, equipped with Dikablis. Navigation instruction were received via the on-board sound system and the whole drive period was recorded. In order to counterbalance for learning and fatigue effect, the sequence of critical situations was permuted between participants. When participants caused an accident, they were not interrupted except that they were unofficially asked for the reason of an accident and the attention focus.

After the trial, each critical situation was replayed to the subject and participants were asked to fill-out situation-specific questionnaires. If subjects were involved in an accident, specific accident questionnaires were given. That way subjective opinions regarding the cause of an accident, attention, mental workload and the reality aspect of the simulation were gathered. As an additional task, subjects had to rank situations according to the subjectively perceived risk. They also had to give their suggestions about what kind of assistance they would like to have in different scenarios. The whole test took approximately an hour. The purpose of the study was not revealed to them in order to avoid experimental bias. Thanks to the flexibility of the simulation environment and due to the fact that the majority of participants encountered the simulator for the first time, none of them realized ahead of time that the testing concerned critical situations.

The primary sample involved 30 subjects. One third did not finish the test due to the simulator sickness. All upcoming data refer to the 20 subjects who did finish the drive. Analyzable subject sample ranged from 21 to 54 years ($\mu = 25.8$, $SD = 7.27$). From that, 19 subjects were male and one subject was female. Although intended, it was not possible to include a representative population of elderly persons due to the legal issues. Also, due to the fact that subjects were not paid for participating, the sample involved mainly students from Technische Universität München. On average, the subjects had a valid driving license of German standard B category for 8.6 years ($SD=7.66$). The driving experience was approximately 10 000 km per year.

For the evaluation, two groups of drivers were formed based on their experience. As experienced drivers were classified the drivers fulfilling one of the following conditions:

- drivers who had a license longer than 4 years and were driving more than 20.000km/year,
- drivers driving between 10 and 20.000km/year and had driving license for more than 7 years,

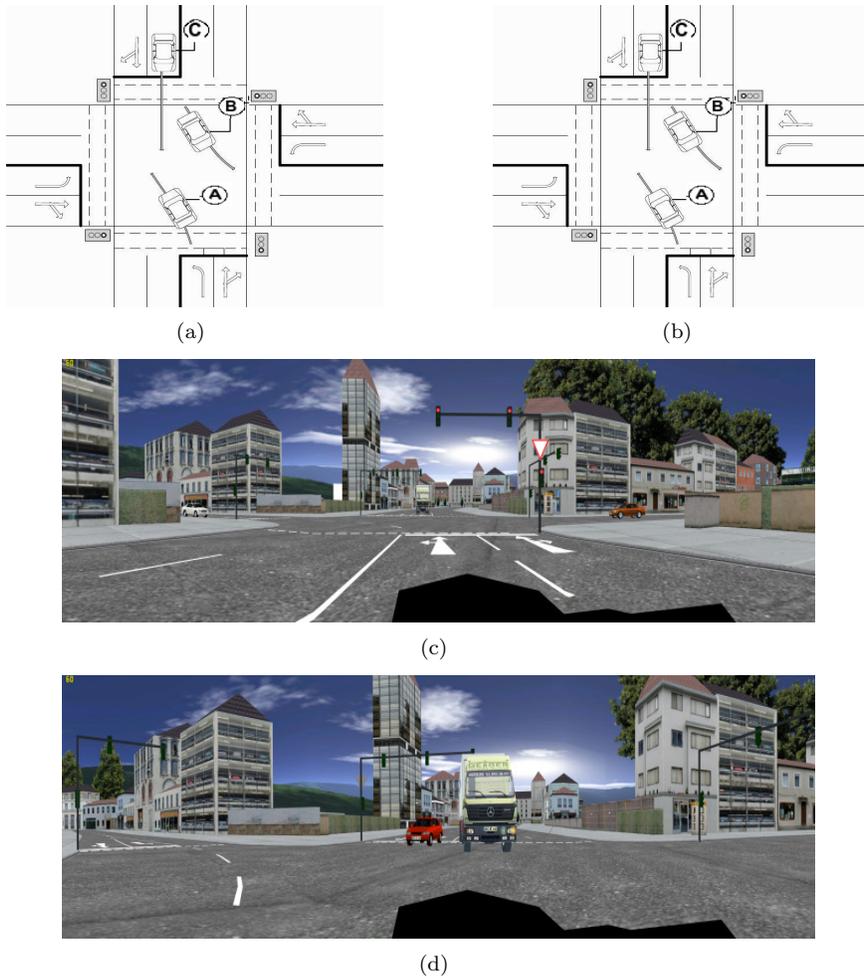


Figure 6: Scenario 1 - *Approach* intersection and *Prepare for turn* phase from: (a),(b) bird's eye view (vehicle A is the driven vehicle and vehicle C presents hazardous object) and (c),(d) driver's perspective

- two more drivers driving between 10 and 20.000km/year and having driver license for 5 years, but driving on every-day basis in urban traffic.

4 Results

One of the goal of this study was to research if a critical scenarios can be created in a way, that every serious error lead to an accident, independent of driving style. Therefore, firstly findings dealing with an accident frequency and its relation to the committed errors are discussed. Subsequently, the analysis of situation awareness by presenting subjective expectations and perception of hazardous objects and risks is given. Finally, the task analysis for each intersection segment was performed and committed errors were classified according to Hacker (1986).

The software and the infrastructure of the driving simulator proved to be very useful for designing realistic critical scenarios in urban environments, concerning both type of errors: when *information is objectively missing* and when *information is not objectively missing*. None of the participants became aware of the purpose of the experiment and all of scenarios were judged as quite realistic. Also, even though, it was not the goal to design common and typical scenarios, the two test persons who have caused an accident in Scenarios 1 and 4, were involved in the same accident-scenario in the real life, respectively.

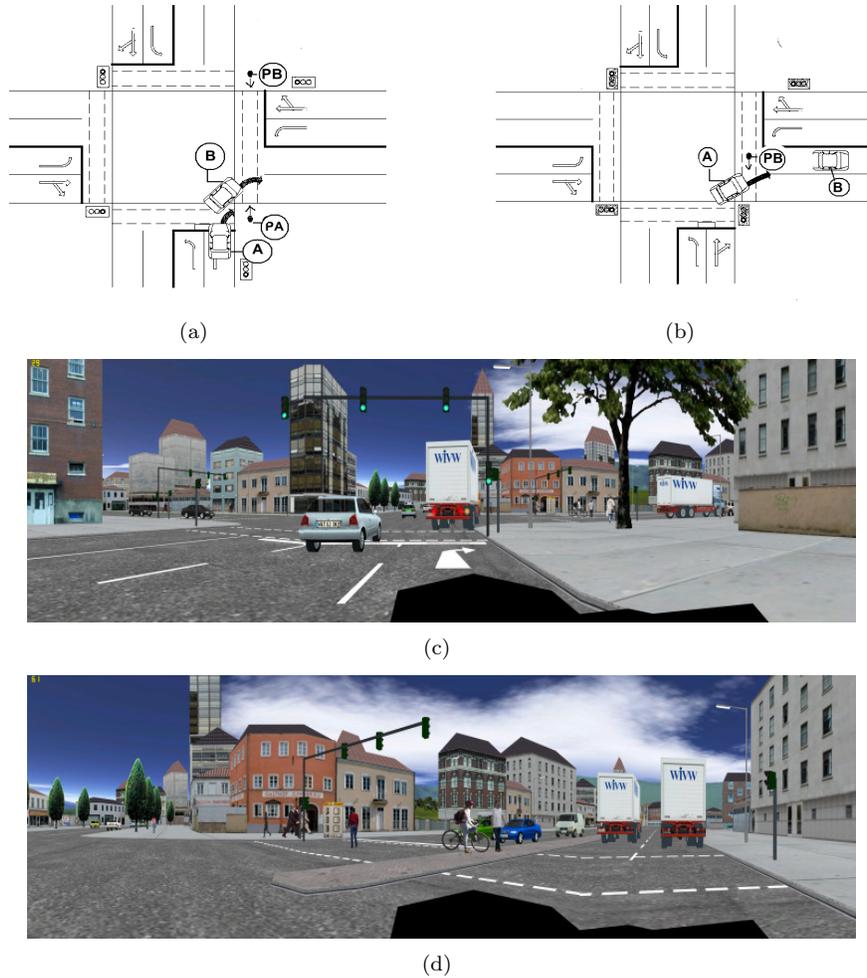


Figure 7: Scenario 2 - *Approach* intersection and *Prepare for turn* from: (a),(b) bird's eye view (vehicle A is the driven vehicle, PB is hazardous pedestrian) and (c),(d) driver's perspective

Accident Frequency and Driver Errors

As seen in Figure 10(a), the highest number of accidents was caused in Scenario 1. The reason that only one accident occurred in Scenario 2 was due to the insufficient control mechanism of the pedestrian in the simulation software. The problem in creating a critical situation with pedestrians is that it was not possible to overwrite restrictions set on them. They have a maximum speed of 7 m/s and an acceleration which cannot be changed. Especially this fixed acceleration prevents sudden pedestrian movement, thus making it nearly impossible to create a hazardous intersection scenario involving pedestrians. In six cases, pedestrian was activated too late, so that the scenario was not triggered at all and participants were not exposed to critical situation. Remarkably, experienced and novices drivers were responsible for almost the same number of accidents (see Figure 10(b)).

Figure 11 depicts a relation between the number of serious errors which did not account for an accident and the number of situations where correct behavior resulted in an accident involvement. As serious errors, which should have resulted in an accident, following errors were considered: for Scenario 1 - not stopping/slowning down at the middle of intersection and not paying any attention to the oncoming traffic; for Scenario 2 - not scanning to the left to check for pedestrian behind the truck in the *Prepare for turn* segment; for Scenario 3 - not stopping/slowning down at the middle of intersection to scan the area behind the parked vehicles and for Scenario 4 - not scanning to the right and forward view while *Prepare for turn* segment and accelerating too fast after executing the turn without scanning for crossing pedestrians.

For Scenarios 3 and 4, it has been clarified that all serious errors resulted in an accident. In Scenario 2, several erroneous behaviors did not account for an accident due to the already mentioned insufficient control mechanism of

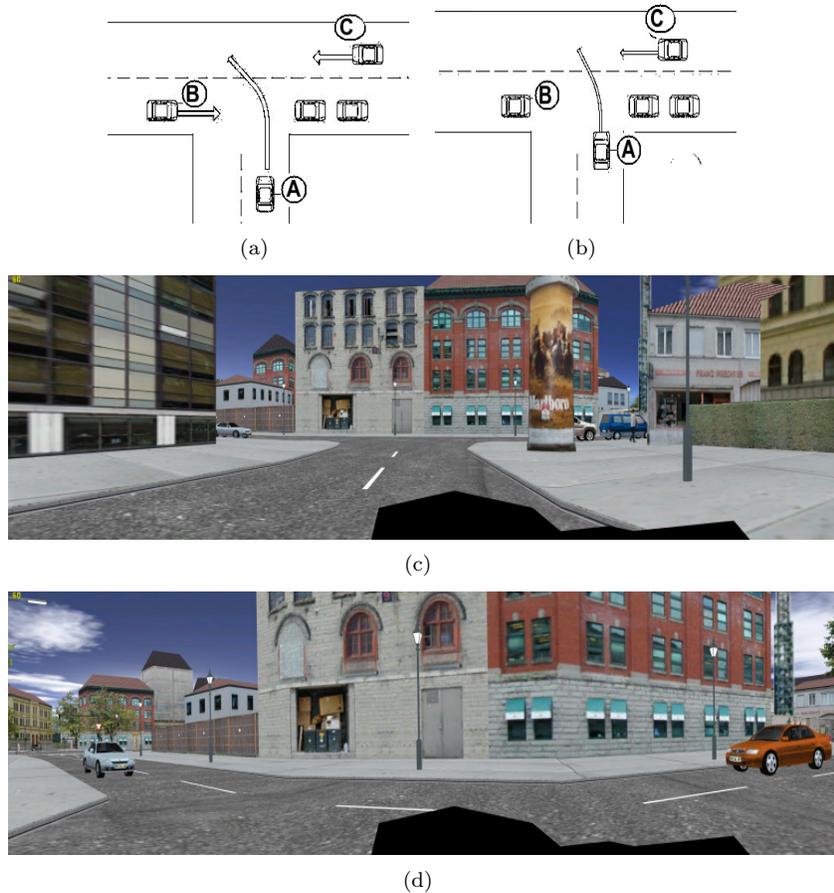


Figure 8: Scenario 3 - *Approach* and *Prepare for turn* from: (a),(b) bird's eye view (vehicle A is the driven vehicle, vehicle C is hazardous object) and (c),(d) driver's perspective

pedestrians. In contrast, in Scenario 1, six correct actions resulted in an accident because of the extremely defensive driving of these subjects. They were moving so slowly into the intersection that the hazardous vehicle, which was synchronized to the driven vehicle, arrived too late to the trigger point and resumed with unrealistic acceleration. Therefore, this unrealistic behavior of the simulation software caused the vehicle C (see Figure 6) to accelerate and crash in the own vehicle, without the driver being able preventig this.

Subjective Expectations and Perception

To investigate aspects of employed inner models concerning expectations and perception of a suddenly appearing hazardous vehicle, several questions were asked. Although, the answers have to be interpreted with attention, as they are a product of rationalization, they can still give an insight into driver inner models.

In Figure 12(a) results on the example of Scenario 1 and Scenario 4 are presented. They illustrate that there is no difference in expectations between occluded and visible hazardous objects. Also, the results from the other two scenarios comply with this conclusion as well. However, they indicate that the majority of subjects do not have correct mental images of the scenarios. Almost half of the participants did not expect a hazardous vehicle in Scenario 1. Several subjects caused an accident even though they both expected and perceived a hazard. Possible reason for this can be inconvenience with a simulator environment and emerging simulator sickness. The subjectively given reason was the low concentration in all the cases. Several subjects stated that although they were still able to react when they perceived the hazard, they were not quick enough to maneuver. Even though, there was no significant difference between experienced and non-experienced drivers, there was a tendency of experienced drivers having less expectations of hazardous objects, even though they evaluated scenarios as more realistic.

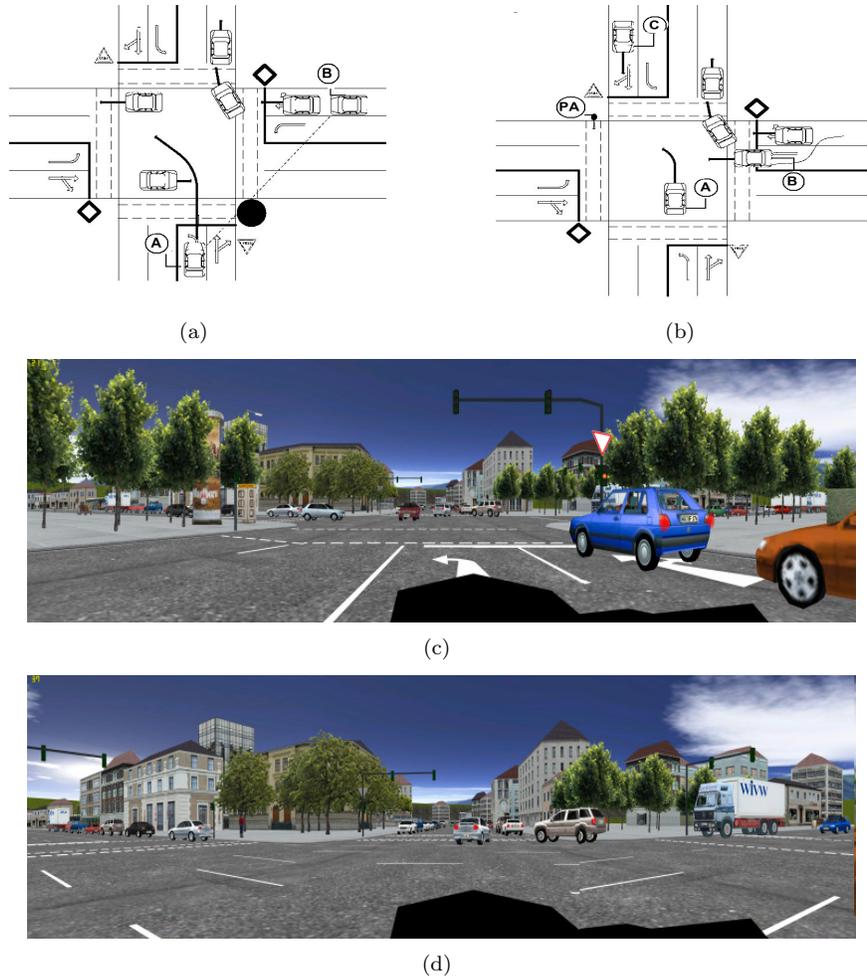


Figure 9: Scenario 4 - *Approach* intersection and *Prepare for turn* from: (a),(b) bird's eye view (vehicle A is the driven vehicle, vehicles B and C and pedestrian PA are possible hazards) and (c),(d) driver's perspective

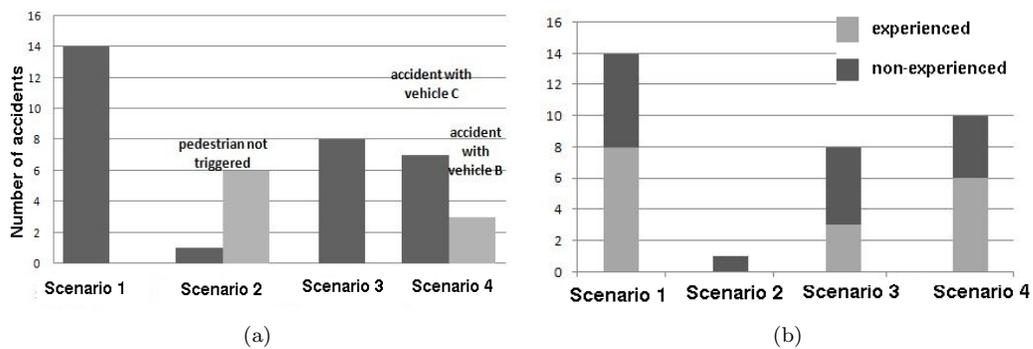


Figure 10: (a) Number of accidents with respect to the intersection scenario. In Scenario 2, hazardous behavior of the pedestrian was not triggered with six subjects (b) Accident frequency with respect to the drivers' experience

Comparison of Subjective Opinions regarding Attention Focus with Glance Recordings

Foveally focusing an object does not necessarily mean that this object is perceived and recognized. In search for look-but-not-see errors, participants were asked about their focus of attention before an accident happened. The discrepancy between subjective answers and objective recordings give an important clue of drivers' situation

	Situation 1		Situation 2		Situation 3		Situation 4	
	<i>correct</i>	<i>erroneous</i>	<i>correct</i>	<i>erroneous</i>	<i>correct</i>	<i>erroneous</i>	<i>correct</i>	<i>erroneous</i>
accident	5	9	0	1	0	8	0	10
no accident	6	0	14	5	12	0	10	0

Figure 11: Relation between the drivers' erroneous behavior and triggered accidents. Grey marked areas present undesirable events of correct driver actions leading to an accident and erroneous actions resulting in no accident

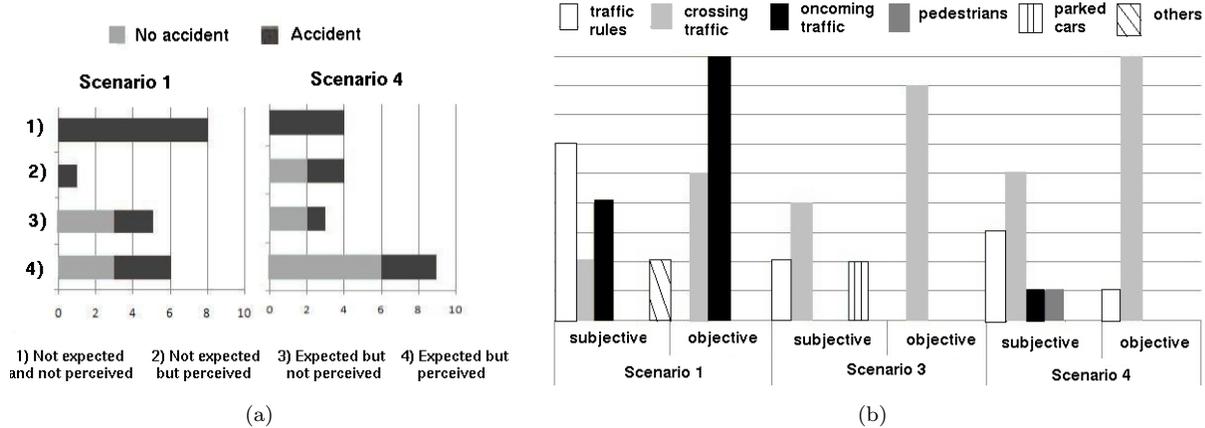


Figure 12: (a) Expectation and perception of hazardous objects with respect to accident involvement, (b) Attention and focus of subjects being involved in an accident at the critical moment: comparison of subjective focus and glance recordings

awareness. In order to get the most ingenuous answer, participants were asked twice about their focus before an accident. First time, just upon the accident, the investigator asked unofficially what happened and where did they look at. The drive was not interrupted and participants were reassured to drive further. These answers were then again compared to the answers from 'after-drive' questionnaires and to the objective recordings of the glances. In Figure 12(b), results concerning Scenarios 1, 3 and 4 are given. Comparison for Scenario 2 is not presented, as in this scenario just one person was involved in an accident. In all three presented scenarios, participants' eyes were focusing either on the oncoming or on the crossing traffic. Opposed to that, subjective attention focus was mainly captured by traffic signs and by understanding the traffic rules. Three participants involved in an accident in Scenario 1 and 4 were foveally focusing the hazardous vehicle without perceiving it, committing the so called look-but-not-see error.

Mental Workload and Subjective Risks

Concerning the mental workload which was induced on the drivers, there was no significant difference between the scenarios. As expected, a slightly higher workload resulted in Scenario 4. Although just one accident was caused in Scenario 2, the subjectively experienced risk was the highest for this scenario, followed by Scenario 1. This indicates that the subjectively experienced risk correlates more with vulnerable traffic participants and occluded objects, than with complex driving tasks. Although, Scenario 4 presents the most demanding traffic situation in which a high number of errors was committed, the subjectively perceived risk of the situation was not high. Likewise, the personal demand for an assistance support correlated with subjectively experienced risk, rather than with the mental workload.

Additionally, participants were asked which part of the driving task caused the highest strain. These results matched the results concerning subjective focus of attention. For subjects who caused an accident, the highest strain was equally distributed between traffic signs, crossing and oncoming traffic. For subjects who were not involved in an accident, the highest strain was induced by understanding traffic rules in all the scenarios. There was no significant difference between groups of experienced and non-experienced drivers regarding the cause of the highest strain.

Task and Error Analysis

For the task and error analysis each intersection was divided into the five spatial segments and the tasks analysis for each of the segments was performed (see Figure 4). The focus was on identifying tasks that were not foveally focused. Not scanning for pedestrians does not necessarily mean that they would not be seen through peripheral vision. However, at intersections, especially with a higher visual load, the probability that objects will be overseen is higher if they are not foveally focused. Such an analysis can also give an insight into drivers' searching strategies and reveal look-but-not-see errors.

In the *Approach* segment, visual behavior in all four scenarios was similar. Drivers were mainly focused on the road ahead. In all scenarios except in Scenario 2, the majority of subjects scanned the area extensively for the hazards. However, in Scenario 2, subjects focused mainly on the vehicle in front. For example, they focused traffic lights much less than in Scenario 1 and mostly oriented themselves according to the leading vehicle. While waiting at the traffic lights, very few subjects viewed the further path.

In the *Deceleration* segment, no serious errors were committed. A lot of subjects did not foveally focus on the crosswalk and changing of the traffic lights. This is especially the case with Scenarios 2 and 4, where drivers mainly oriented themselves according to the leading vehicle.

In the *Intersection entry* segment, it was very common that drivers did not directly pay attention to the crossing pedestrians. This was especially the case in Scenario 4 (see Figure 13). Novices, in particular, were disregarding this task. Also, in all scenarios, very few drivers checked for vehicles that did not have the right of way. In the Scenario 4, the scenario with the highest visual load, all intersecting roads were checked several times and performance was close to ideal for all participants. This indicates that vulnerable traffic participants have the lowest priority when searching for hazards.

In the *Prepare for turn* segment, in the Scenario 1, the most serious errors were not paying attention to the oncoming traffic, which was omitted by almost half of the subjects and not slowing down at the middle of intersection to yield the way to the oncoming traffic. In the Scenario 2, the most of drivers checked just for pedestrian to the right side of the street, but not to the left. In the Scenario 3, one fourth of the subjects did not check for the vehicles having a right of way. Also, very few subjects scanned for the vehicles not having a priority in all the scenarios, especially from the direction opposite of the further driving path.

In the *Execute turn* segment, scanning the area for hazards was noticeably reduced by almost all subjects. Dedicated scanning for pedestrians when leaving the intersection was omitted to a higher extent than at the *Intersection entry*.

Fisher's exact test revealed no significant differences between experienced and non-experienced drivers. Yet, an important difference between the cognitive strategies of these two groups is that non-experienced drivers scanned wider areas, but did not check for hazards foveally. Scanning reduction was especially observable with the task of searching for the traffic participants without right of way and pedestrians.

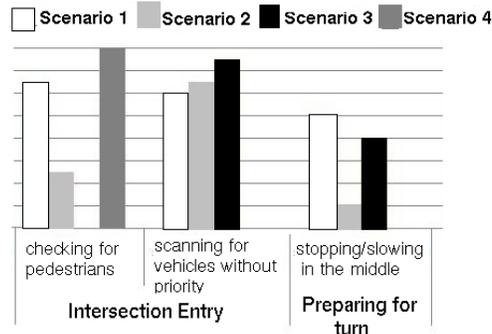


Figure 13: Some of the omitted tasks in *Intersection Entry* and *Prepare for turn* segments. In Scenario 4, very few subjects scanned for pedestrians but all intersecting roads were carefully checked

Thanks to the specifically designed questionnaires and the recordings of eye glances, the reasons for the errors leading to accidents could be determined. In the Scenario 1, 10 subjects caused an accident and 9 of them did not stop at the middle of intersection; 3 of them were driving too hastily and 6 did not brake after focusing hazardous vehicle. Three participants reported that they have seen hazardous vehicle when approaching intersection, but forgot it while waiting at the traffic lights (see Figure 14). In general, swayed focus and attention was the most common

reason for accident occurrences. Hasty driving, without paying enough attention is also observable in the first three scenarios. To that, most of the subjects failed to react promptly.

In the Scenario 4, even three participants were focusing hazardous vehicle but did not anticipate it. This indicates that in complex situation focus does not mean attention. Drivers are building mental model of situation and this model also includes other vehicles and their movements. The model is refreshed with foveal focuses, but if the scenario is complex, cognitive resources are often fully allocated to mental image 'update'. Therefore, in spite of the fact that in Scenario 4 the performed cognitive behavior was the closest to ideal one, committed errors were related to the drivers cognitive limits and therefore present the most risky errors.

	inside distraction	look but not see	wrong focus	information forgotten	overload	not braking	not slowing/stopping at the middle of intersection	conscious violation of speed
Scen. 1	4	1	5	3		6	9	3
Scen. 2	1		6	1		1	4	2
Scen. 3			6			4	8	3
Scen. 4	5	3	5		4	3	3	4

Figure 14: Classification of errors committed at *Intersection entry* and *Execute turn* segments

5 Conclusion and Further Work

In order to identify requirements for ADAS at intersections, causes of drivers' erroneous behavior should be determined. For that reason, drivers should be exposed to a situations which will provoke such a behavior. Thereupon, two methodological issues arise: experimental design and the appropriate choice and implementation of such a scenarios.

In the conducted study, driver situation awareness and inner mental models at critical intersection scenarios are examined in order to diagnose the spots with the most common driver errors and to examine applied strategies. This was done by analyzing the driving and cognitive behavior of 20 subjects in the four independent intersection scenarios implemented in the static-based driving simulator. The novelty of the study is that this analysis was performed with a seemingly realistic simulation environment which offers full control of traffic participants and partial control over pedestrians as well as full control over environmental appearance. Additionally, the light-weight eye tracking system enabled very precise analysis of cognitive behavior. The scenarios were carefully designed in a way to provoke two types of driver errors: when *information is objectively missing* and when *information is not objectively missing*. Scenarios were designed in a way not to resemble the usual mental models of the majority of the drivers.

Simulation environment proved to be suitable for implementation of critical scenarios: both types of error were committed in the chosen scenarios. Also, it was achieved that majority of serious errors led to an accident, except for scenarios including pedestrians. Improvement of the software can be done by having a better control over pedestrians and by implementing the possibility of synchronizing other vehicles based on an algorithm dependent on the vehicle's own speed. At the moment just a static synchronization function is available.

The results indicate that the errors when information is objectively missing appeared mainly because of an inappropriate mental model of the current situation. It also seems that mental models are not built upon ideal behavior, but on the base of experience. Experienced drivers committed more serious errors than the non-experienced drivers. Nonetheless, non-experienced drivers performed less than ideally in comparison to the experienced ones. Causes for the errors when information is not objectively missing lay mainly in human cognitive limits.

The analysis of an experiment gave, as well, an insight into applied cognitive strategies. Based on the observation and the results a several hypotheses can be made. One hypothesis states that drivers mainly focus on the current intersection segment and that the anticipation of the further situational development is very low. Another hypothesis is that the drivers' attention is mainly directed towards a planned trajectory. The consequence is that if the situation is complex enough and attention is not caught by objects appearing in the peripheral view, some area of the intersection may stay unobservable and unnoticeable. A further hypothesis is that the existence of a leading vehicle changes the drivers' strategy in a way that the drivers orient themselves mainly according to the leading vehicle, reducing attention to the other segments of the driving task. This study also revealed that a lot of subjects did not check for possible hidden traffic participants. This especially pertains to pedestrians. Pedestrians and traffic participants not having the right of way are expected to be seen peripherally and drivers, especially novices, are not directly searching for them. Another hypothesis that can be made is that drivers pay the least amount of attention

to the *Execute turn* segment. Concerning attention, it can also be concluded that the more demanding the situation is, the more attention the driver is allocating to the task. Especially for demanding tasks, conscious risky actions are rarely the cause of accidents but in these situations drivers' cognitive limits are easily reached.

The results also showed that drivers require support more for situations with sight obstruction and vulnerable traffic participants than the assistance for complex driving tasks. This requirement correlates more with subjectively experienced risk, than with the mental workload. The mental workload is connected to the complexity of the driving task. In such demanding situations, traffic sign assistance would meaningfully contribute to its reduction. This does not refer to the traffic sign recognition assistance system, rather to the assistance which is in critical moment informing the driver which direction they should yield the right of way to, as it seems that having this fact unceasingly on the mind occupies driver cognitive capacities to a very high extent. This can be especially problematic when they simultaneously have to search for hazards or to process any other kind of information.

As a part of the further work, the stated hypotheses will be further developed, evaluated and analysis of sequential visual movements will be performed. Based on the results, inner models for different intersections scenarios will be defined in the form of computational simulation of drivers' cognitive behavior at intersections.

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