CH-LSTTM: A Taxonomy of Traffic Hazards

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***Abstract*—During driving, drivers must interact with various objects in the highly dynamic driving environment, in which they need to perceive the traffic hazards and handle safety-critical scenarios. Previous studies have proved the importance of drivers' hazard perception skills and designed corresponding driver training programs. However, due to the lack of a suitable taxonomy for hazards, most driver training programs on hazard perception are simply a collection of various hazardous scenarios but do not guide drivers' hazard perception skills in a systematic way. The existing taxonomies of hazards were mainly based on the characteristics of hazards but did not take the hazard perception procedures into consideration, which can hardly be applied to improve drivers' hazard perception skills. Therefore, in this study, we proposed a taxonomy of traffic hazards based on an analysis of hazard perception procedures. Overall, a four-element taxonomy of traffic hazards (i.e., CH-LSTTM) was proposed, in which the Cues (single-element-based, multiple-element-based, and no-element-based), Hazards (visible vs. invisible), Link Strength (LS, which accounts for the uncertainty between the cues and the hazards during the hazard development process), and Time to Materialization (TTM, which indicates the imminence level of the hazard) were considered. We demonstrated the capability of the proposed taxonomy in depicting and categorizing real-world traffic hazards through a naturalistic driving case study. The proposed taxonomy can support the optimization of driver training programs to improve their hazard perception skills.**

Keywords—Traffic Hazards, Hazard Taxonomy, Driver Training, Hazard Perception

I. INTRODUCTION

Hazards were generally defined as "sources of danger that exist in the environment" [1]. More specifically, in the driving domain, researchers referred hazards as "any object, situation, occurrence or combination of these that introduces the possibility of the individual road user experience harm" [2]. To take appropriate actions against various hazards on roadways and ensure driving safety, drivers must maintain situation awareness of the traffic environment, i.e., drivers need to perceive, understand, and predict the hazards in the dynamic driving environment correctly [3]. As a key driving skill, drivers' ability to perceive hazardous situations (i.e., hazard perception capability) in the driving environment has been highlighted by existing research, i.e., drivers with better hazard perception skills are acknowledged as being less likely to be involved in crashes [4].

Thus, in addition to focusing on basic vehicle operation skills, many states or countries have also started to evaluate drivers' hazard perception skills on the road. For example, the driver licensing procedures in the UK had included the hazard perception test since 2002, which has successfully reduced crash rates among novice drivers [5]. Researchers also explored different hazard training methods for drivers [6]–[9]. For example, using video-based road commentary training, Isler et al [10] found that young drivers' hazard perception capabilities could be improved to the level of experienced drivers after training. Horswill et al [11] found that even the hazard perception performance of highly experienced drivers could be improved with a simple 20 min of video-based training. Horswill et al [12] also found that providing artificial feedback (e.g., video-based feedback and graph-based feedback) on individual drivers' performance in hazard perception tests could improve drivers' hazard perception skills. In a more recent study, Horswill et al [13] found that an online training course designed to minimize the rate of forgetting could lead to an enduring effect on the hazard perception skill of novice drivers. It should be noted that the effectiveness of the training is highly dependent on the design of the training materials (e.g., hazard contents) [14]. To the best of our knowledge, existing studies either developed their own training materials [7], [15], [16], [17] or used previously established hazard perception training programs [18], [19], [20], [21], such as the Risk Awareness and Perception Training (RAPT) program [22]. These hazard perception training programs selected a limited number of hazards that can happen on the road but did not organize the hazards in a systematic way. Thus, they may not work well if drivers encounter new un-trained hazardous scenarios.

The research in the education domain suggests that a well-established framework may facilitate enduring memory of the information and support the application of the knowledge even when new scenarios are encountered [23]. Thus, a systematic taxonomy of hazard scenarios may support drivers' understanding and memory of hazards and alleviate the decaying effect of hazard perception training over time [18]. Therefore, a taxonomy of traffic hazards on roadways could be helpful to guide the design of better drivers' hazard perception training programs.

A number of taxonomies of hazards have been proposed in previous studies, for the training of human drivers or for the test of driving automation. For example, depending on different instigators of hazards, the hazards in driving were categorized into different types: driver hazards (e.g., distraction, alcohol, and drug), ego-vehicle hazards (e.g., sub-system malfunction), natural environment hazards (e.g., fog and snow), and traffic hazards (e.g., other road agents violates the traffic rules) [24]. Differentiated by the threat imminence level, the hazards in driving include immediate hazards (i.e., hazards that require immediate response) and non-immediate

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This research was funded by the National Natural Science Foundation of China (Grant No. 52202425) and partially by the Guangzhou Municipal Science and Technology Project (No. 2023A03J0011), and the Guangzhou Science and Technology Program City-University Joint Funding Project (No. 2023A03J0001).

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hazards (i.e., hazards that have not materialized yet but required attention) [25]. The non-immediate hazards can be further divided into overt non-immediate hazards (i.e., visible) and covert non-immediate hazards (i.e., invisible) based on the visibility of hazards [1]. Crundall et al [14], [26] classified the hazards into behavioral prediction (BP) hazards and environmental prediction (EP) hazards based on the relationship between the precursor of the hazard and the hazard itself. On top of BP and EP, the anticipatory driving scenarios were further proposed, in which the perception of the hazards relies on the dynamic relationships of road agents [27], [28]. However, the above-mentioned taxonomies were based on the characteristics of hazards, which overlooked the cognitive procedures and information requirements for the perception of hazards. Thus, they can hardly support systematic training of drivers and the generation of hazardous scenarios.

Thus, to bridge the research gaps, we aim to achieve the following objectives in this paper:

1) Discuss the overview of the hazard perception process and the key concepts related to it.

2) Propose a systematic taxonomy of traffic hazards by taking the information required for hazard perception into consideration, given that traffic hazards have a substantial impact on traffic safety.

3) Discuss the applicability of the proposed taxonomy through a case study based on around 100 hours of video data recorded in a naturalistic driving study.

II. HAZARD PERCEPTION PROCESS

To propose the taxonomy, it is necessary to first define the hazard perception procedures. According to the framework of situation awareness (SA) proposed by Endsley [3], theoretically, human drivers should first perceive the elements in the current driving environment (i.e., Level 1 SA), then understand the current driving situation (i.e., Level 2 SA), and finally anticipate the future status of elements in the driving environment (i.e., Level 3 SA). Previous research also described the driving task as an uncertainty reduction procedure – while driving, drivers keep seeking information to reduce the uncertainty in predicting other road agents' behaviors before a decision is made [29]. Combining these two theories, in the study, we describe the hazard perception procedures as a procedure in which drivers reduce the uncertainty in their perception of the traffic development based on the extracted information from road elements they perceive. This definition incorporates both the definitions of hazard perception ("the process of detecting, evaluating and responding to dangerous events on the road that have a high likelihood of leading to a collision") [14] and hazard prediction ("the ability to read the road and anticipate forthcoming events") [30], but further explained the connection of each key components in the hazard perception procedure, i.e., the information flowed from the perception of the road element (Level 1 SA), to the understanding of the element to extract information (Level 2 SA) and then to the anticipation of the traffic development (Level 3 SA). The prediction of a single hazard based on the road element can be illustrated in Figure 1.

As shown in Figure 1, the information extracted from a single traffic element may be used to form multiple cues (e.g., a traffic light may provide information regarding the future motion of multiple vehicles on the road) and information from multiple traffic elements may form a single cue (e.g., the relative motion of the two vehicles may indicate a potential braking behavior). It should be noted that the cues may have strong and weak associations with a hazard and may even provide conflicting information regarding the probability of a hazard. The formal definitions of Cue and Hazard are as follows. We also defined two concepts to describe the relationships between the cues and the hazards, i.e., Link Strength (LS), and Time to Materialization (TTM).

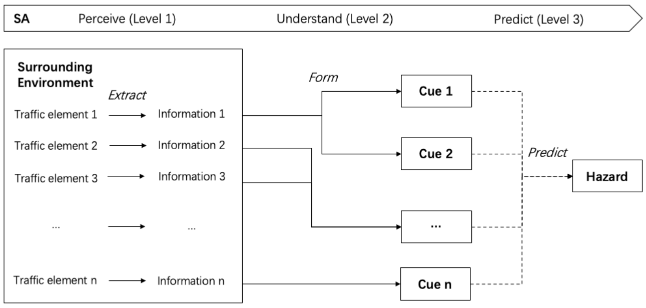


Fig. 1. Framework of Information Reduction Process

A. Hazard

The hazard is defined as any object that is on the path or will be on the path of the ego vehicle if the motion state of the ego vehicle does not change. Crundall et al [14] categorized two types of hazardous scenarios (i.e., BP and EP), in which the hazard itself was visible in BP while the hazard in EP was usually obscured by other objects in the driving environment and hence invisible. Therefore, following previous studies, we categorized the hazard into two types: visible hazard and invisible hazard.

B. Cue

In this study, cues are defined as the information extracted from the road element(s) (including the objects, infrastructures, events, environmental conditions, etc.) in the traffic scenario, which can signal the occurrence of hazards. The role of cues during the hazard perception process is to provide information about the hazard and reduce the uncertainty of hazard anticipation. For example, in the scenario in Figure 2, the cue is that the pedestrian might walk into the road, which can be extracted based on the posture and eye movement of the pedestrian.

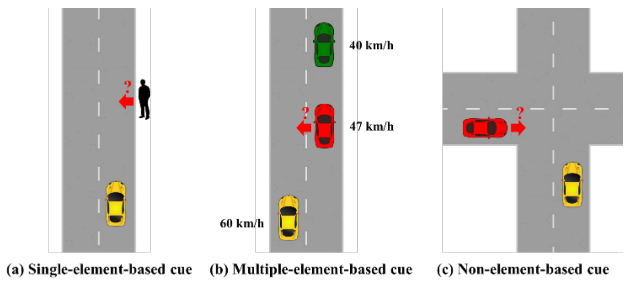


Fig. 2. Examples of Multi-element-based Cue and Single-element-based Cue

Based on the number of pieces of information that constitute a cue, the cues can be classified into single-element-based cues (S-cues), multiple-element-based cues (M-cues), and non-element-based cues (N-cues). Figure 2(a) is an example of the S-cue, where the pedestrian's intention to walk into the road can be extracted based on the status of the pedestrian alone. In contrast, Figure 2(b) illustrates a situation where the red car might merge into the left lane and become a hazard to the ego vehicle. In this scenario, neither the red car nor the green car alone can provide enough information to inform the evolution of traffic development. Instead, the motions of the two vehicles need to be combined to form an M-cue, based on which the action of the red car can be inferred. Figure 2(c) shows an example of the N-cues, where the absence of the traffic light indicates that another vehicle might also enter the intersection anytime.

It should be noted that perception of S-cues, M-cues, and N-cues of hazards may claim different mental resources. Typically, the extraction of M-cues is assumed to be more cognitively demanding compared to S-cues as drivers need to perceive multiple road elements and understand their connections (e.g., relative movements of road agents) to extract the M-cues. Thus, the M-cues are more challenging for drivers to perceive compared to S-cues. The N-cues, however, are the most difficult and rely on the pre-knowledge of the scenario, given that knowing what is missing is difficult.

C. Link Strength (LS)

Given the uncertainty during the process of hazard development, the link strength refers to the strength of association between the cues and the hazards. In most previous taxonomies of hazards, the association between the cues and the hazards was not considered. Although Crundall et al [14] differentiated the BP and EP using the direct or indirect links between precursors and hazards, which failed to capture more diverse traffic situations. For example, in a single scenario, multiple cues can provide even conflicting information (e.g., in a scenario, the closing distance between two vehicles in the adjacent lane indicates a lane change but a solid line reduces the chance of lane change). Therefore, we decompose the overall probability of a hazard (i.e., $p(hazard)$) into the LS between each cue and the hazard, as shown in Equation (1):

$$p(hazard) = 1/(1 + e^{-\sum_{n=1}^{N} LS(n)}) \quad (1)$$

In the equation, $LS(n)$ is the LS between the nth cue and the hazard. The LS is a continuous variable with possible values ranging from -1 to 1. For example, the LS between a solid line and a vehicle changing the lane (i.e., the probability that a vehicle cutting in front given the existence of the solid line) is negative, as a solid line means no crossing. On the contrary, the LS between the reduced distance between the red and green vehicles in Figure 2b and the red vehicle merging left is positive. The sum of the LS of all cues is a value that ranges from negative infinity to positive infinity. Thus, we adopted the sigmoid function to map the sum of LS into the range between 0 and 1, so that we can depict the probability of the hazard given all cues in the traffic scenarios.

D. Time to materialization (TTM)

In the field of traffic safety, the time to collision (TTC) has been commonly used to identify abnormal driving behavior and evaluate the crash risk [31]. The TTC was defined as "the time that remains until a collision between two vehicles would have occurred if the collision course and speed difference are maintained" [32]. Typically, smaller TTC values are associated with more safety-critical situations, while larger TTC values indicate safer situations.

Similar to TTC, the time to materialization (TTM) refers to the time between the moment of cue onset and the time at which a hazard materializes [33]. Here, the cue onset is when the information regarding the materialization of the hazard can be extracted. Once a hazard is materialized, it means the ego vehicle is on a collision course with the hazard, and braking or steering maneuvers of the ego vehicle are required to avoid collisions. Theoretically, all objects in the driving environment could provide cues regarding specific hazards; however, the TTM values of different hazards might be different. For example, for some imminent hazards (e.g., a roadside pedestrian suddenly steps onto the road), the TTM values are small, which requires drivers to respond through immediate actions (e.g., braking or steering). For some non-imminent hazards (e.g., a slow lead vehicle in the lane), the TTM values are relatively large; thus, drivers may not take action until the TTM reaches a threshold. Specifically, the TTM of unpredictable immediate hazards (e.g., an object suddenly falling from the lead vehicle) is zero, as the cue is extracted from the hazardous object. In contrast, all non-hazardous objects in the driving environment can be regarded as having a TTM of near positive infinite as they would not become hazards "forever". Therefore, the TTM can be used as a metric for evaluating the imminence level of the potential hazard. Finally, it should be noted that the TTM is not equal to TTC. For example, when a pedestrian is walking towards the road, the TTC is infinite before the pedestrian walks into the roadway; but the TTM is not infinite.

III. A TAXONOMY OF TRAFFIC HAZARDS: THE CH-LSTTM

Based on the above-mentioned elements in a hazardous scenario, as shown in Figure 2, drivers need to extract the relevant information from the road element to form cues, where the links between the cues and the hazard are based on the LS and TTM. In the dynamic driving environment, drivers would seek more information to update the LS and the TTM would keep decreasing with the development of the scenarios. Thus, we propose the following taxonomy for hazardous scenarios. In the taxonomy, the cues and the hazards are categorical variables, while the LS and the TTM are continuous variables. To better illustrate the proposed taxonomy for categorizing different hazards, here we simplified the LS and TTM by discretizing them. Specifically, the LS was categorized into strong positive (the hazard is very likely to materialize given the cue), weak (the hazard may or may not materialize given the cue), and strong negative LS (the hazard is very unlikely to materialize given the cue), while the TTM was categorized into latent (>0) and imminent (=0) TTM. Therefore, by considering the four elements, we have 36 (i.e., 3 cue types * 2 hazard types * 3 LS types and 2 TTM types) types of hazards. We name this CH-LSTTM (i.e., Cue, Hazards, LS, and TTM) taxonomy.

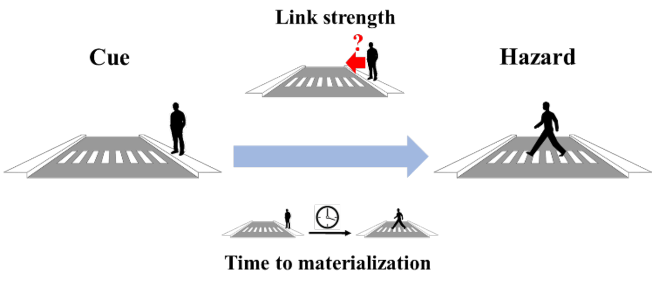


Fig. 3. Four Elements in the Proposed Taxonomy

Table I presents all possible types of hazards based on the CH-LSTTM taxonomy. Among the 36 types of hazards listed in Table I, 24 of them are not logically reasonable for two reasons: firstly, the hazard with imminent TTM (the hazard is already materialized and in the path of the ego vehicle) must be visible and have strong positive LS; besides, it is impossible to have strong LS if the hazard is invisible or the cue is non-element based (i.e., N-cue). Therefore, we end up having 12 types of traffic hazards.

TABLE I. HAZARDS TYPES BASED ON THE CH-LSTTM TAXONOMY

No.	Cues	Hazards	LS	TTM
1	S-Cue	Visible	Strong positive	Latent
2			Strong positive	Imminent
3			Weak	Latent
4			Strong negative	Latent
5	S-Cue	Invisible	Weak	Latent
6	M-Cue	Visible	Strong positive	Latent
7			Strong positive	Imminent
8			Weak	Latent
9			Strong negative	Latent
10	M-Cue	Invisible	Weak	Latent
11	N-Cue	Visible	Weak	Latent
12	N-Cue	Invisible	Weak	Latent

IV. TYPICAL TRAFFIC HAZARDS: A CASE STUDY

To further demonstrate the proposed taxonomy and summarize the representative traffic hazards, we conducted a case study by extracting the traffic hazards based on the recorded videos in a naturalistic driving dataset.

A. Data description and hazard extraction

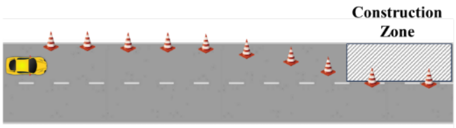
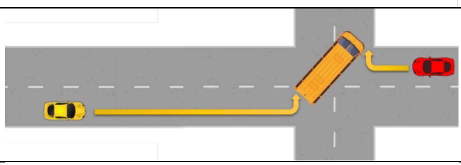
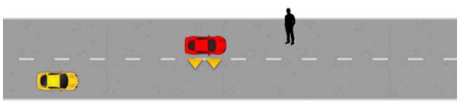
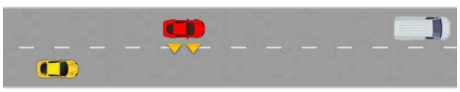
The road video data used in this case study was recorded by a company operating autonomous heavy trucks in China. The video data was collected at a frequency of 20 Hz. Figure 4 provides some screenshots of the road video data. To extract the traffic hazards from the videos, a researcher in the transportation safety field independently inspected the videos and marked the hazardous scenarios.

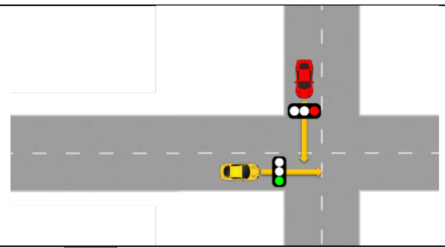
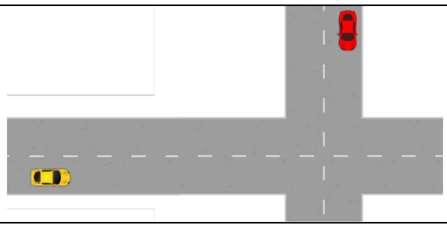
Fig. 4. Illustration of the Road Video Data

B. Examples of representative hazards

We present the hazardous scenarios extracted from the videos in Table II, illustrating all types of hazards listed in Table I. As the original videos contain confidential business information, only sketches of traffic hazards are provided. For better readability, we only present single-hazard scenarios. However, multiple hazards can occur simultaneously and can be captured by our taxonomy.

TABLE II. EXAMPLE FOR EACH TYPE OF HAZARD

Scenarios	No.	Type of cue: traffic element to extract the cue	Hazard	Relationships
	1	S-cue: Turning signal of the red vehicle	Visible Hazard: The red vehicle	LS: Strong Positive TTM: Latent
	2	S-cue: The red is getting close to the dashed line		LS: Weak TTM: Latent
	3	S-cue: The roadblocks	Visible Hazard: The construction zone	LS: Strong Positive TTM: Imminent
	4	S-cue: Solid line	Visible Hazard: The red vehicle	LS: Strong Negative TTM: Latent
	5	S-cue: The orange vehicle	Invisible Hazard: The red vehicle	LS: Weak TTM: Latent
	6	M-cue: The closing distance between the red vehicle and the person that suddenly walk onto the road (too close to stop)	Visible Hazard: The red vehicle	LS: Strong Positive TTM: Latent
	7	M-cue: The closing distance between the red vehicle and the traffic ahead	Visible Hazard: The red vehicle	LS: Strong Positive TTM: Imminent
	8	M-cue: The closing distance between the red vehicle and the white vehicle	Visible Hazard: The red vehicle	LS: Weak TTM: Latent

	9	M-cue: The red light for the ego vehicle and the green light for the ego vehicle	Visible Hazard: The red vehicle	LS: Strong Negative TTM: Latent
	10	M-cue: The bush and the sign “Ramp Ahead” (indicating there is a ramp behind the bush and a vehicle might run out)	Invisible Hazard: The red vehicle	LS: Weak TTM: Latent
	11	N-cue: The absence of zebra crossing (indicating that the person should not cross here)	Visible Hazard: The person	LS: Weak TTM: Latent
	12	N-cue: The absence of traffic lights (indicating that there is a chance that the red vehicle might run into the intersection directly)	Invisible Hazard: The red vehicle	LS: Weak TTM: Latent

V. Discussion

To help human drivers identify and respond to traffic hazards, it is essential to understand the underlying patterns of traffic hazards. In this paper, a four-element taxonomy of traffic hazards (i.e., CH-LSTTM) was proposed, in which the cues, the hazards, the link strength, and the time to materialization were considered. By categorizing hazards in a systematic manner, the CH-LSTTM taxonomy can provide a framework for developing more effective training programs for driver education.

Although a variety of traffic hazard taxonomies have been proposed in previous studies, the CH-LSTTM taxonomy differs in several ways. Firstly, the CH-LSTTM is based on the procedures of hazard perception and the development of hazard development. Thus, in addition to classifying different types of hazards on the road, the CH-LSTTM also provides a framework for estimating the difficulty in detecting different types of hazards and enables the analysis of the cognitive procedures in hazard perception. Further, the CH-LSTTM is compatible with both previous hazard taxonomies and the cognitive models in explaining hazard perception. For example, Stahl et al [34] proposed that experienced drivers can use comparative analysis to quickly identify hazards, while the novice relies on inductive analysis. In the CH-LSTTM, this can be explained as that the experienced drivers used heuristics to estimate the p(hazard); while the novice had to estimate the p(hazard) by considering all LS. It is also possible that experienced drivers are better at extracting the information from the road element. A follow-up study is needed to better understand the mechanisms explaining experienced drivers’ superior performance in anticipating hazards. Further, by introducing two continuous variables (LS and TTM), our taxonomy can also serve as the basis for the development of computational models; although future empirical research is needed to validate our taxonomy, further update the equation describing the relationships and quantify the values of these continuous variables.

Our taxonomy can also better guide the training of the drivers for hazard perception skills. By categorizing hazards in a systematic manner, the CH-LSTTM taxonomy can help identify the specific types of hazards that are more common or critical in certain driving environments, allowing for targeted training and education. For example, a driver training program for urban areas could put more focus on invisible hazards and M-cues as urban roads are often crowded with pedestrians, vehicles, and many non-road users with mutual occlusions. Further, instead of randomly presenting the hazardous scenarios to drivers, the training program can specifically focus on different components of the hazardous scenarios, which may improve drivers’ capability to handle new scenarios that they have not encountered. For example, the correct estimation of the link strength is the basis for hazard perception. The perception of the link strength may only improve with driving experience if not trained specifically. Similarly, to extract the M-cues, the drivers will need to know what should be there in the driving scenario, which is also highly experience-dependent and may rely on long-term memory. Thus, the drivers’ capability to anticipate M-cues-based hazards may rely on both their driving experience and their cognitive capabilities. Future research may further verify our model and taxonomy.

VI. Conclusion

In this study, we have proposed a four-element taxonomy of traffic hazards (CH-LSTTM) that accounts for cues, hazards, link strength, and time to materialization. This taxonomy is proposed based on a new description of the hazard perception procedure, which takes the information flow into consideration. A case study based on naturalistic driving data has proved the capability of the CH-LSTTM taxonomy in characterizing real-world traffic hazards. By providing a systematic framework for categorizing traffic hazards, the CH-LSTTM taxonomy enabled the development of more effective driver training programs tailored to specific hazard scenarios, ultimately enhancing drivers' hazard perception abilities. Overall, with the CH-LSTTM taxonomy, we may better understand the cognitive mechanisms behind the hazard perception skill and predict drivers' performance under different hazardous scenarios. Future empirical research is needed to validate the proposed hazard perception procedure and the CH-LSTTM taxonomy.

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