Exploring the Dynamic Decision-Making Process of Drivers in Safety-Critical Scenarios through Hierarchical Drift Diffusion Models

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I. INTRODUCTION

Drivers' decision-making processes affect collision occurrence and injury severity in safety-critical scenarios at different levels of highly automated vehicles (HAVs). Current driver behaviour models are often data-driven [1] or based on fundamental rules [2] and have not fully deciphered the perceptual decision-making process of drivers. In safety-critical scenarios, the driver's perceptual decision-making is a complex and dynamic cognitive task. Drivers must quickly identify potential hazard signals and decide on the best course of action, such as changing lanes or emergency braking, within a short timeframe. Understanding the drivers' perceptual decision-making mechanisms and avoidance kinematics is vital for guiding the development of collision-avoidance algorithms, optimising occupant protection, and reducing human injury risk [3]. Evidence accumulation models (EAMs), such as the Drift Diffusion Model (DDM), describe how information is processed during decision-making, with a decision being made when accumulated information exceeds a specific threshold [4]. These models are particularly beneficial for comprehending how humans make quick decisions under safety-critical conditions. As a preliminary investigation, this study uses the Hierarchical Drift Diffusion Model (HDDM) to explore the role of EAMs in explaining drivers' perception response times (PRT) and characterising their decision-making processes.

II. METHODS

Drivers' perceptual decision-making processes can be understood and analysed through the DDM (Fig. 1 (b)) and computational modelling to assist in comprehending the brain's mechanisms during the decision-making process in safety-critical scenarios. DDM framework posits that decisions arise from a noisy evidence accumulation process. Evidence is accumulated over time until it reaches a certain threshold, which involves a trade-off between decision time and accuracy. DDM is characterised by four primary parameters (Fig. 1(b)): drift rate, representing the rate of evidence accumulation; decision threshold, indicating the threshold of information accumulation required before making a decision; non-decision time, encompassing time for perception and action preparation; and starting point, the initial position of information accumulation that reflects prior bias.

HDDM represents an advanced application of DDM. It employs Bayesian methods for parameter estimation that extend beyond considering parameters in a singular decision-making process. Its hierarchical structure considers individual differences and variations across different experimental conditions (Fig. 1(c)), offering a more profound understanding of the cognitive processes involved in decision-making. Data on driver responses in safety-critical scenarios were collected from 24 participants through driving simulator experiments, yielding 773 valid cases (Fig. 1(a)). Further experimental details are available in [5]. We determined the parameters of the HDDM regarding drivers' PRT in safety-critical scenarios and initiated a preliminary exploration of the physical significance of model parameters in explaining drivers' decision-making.

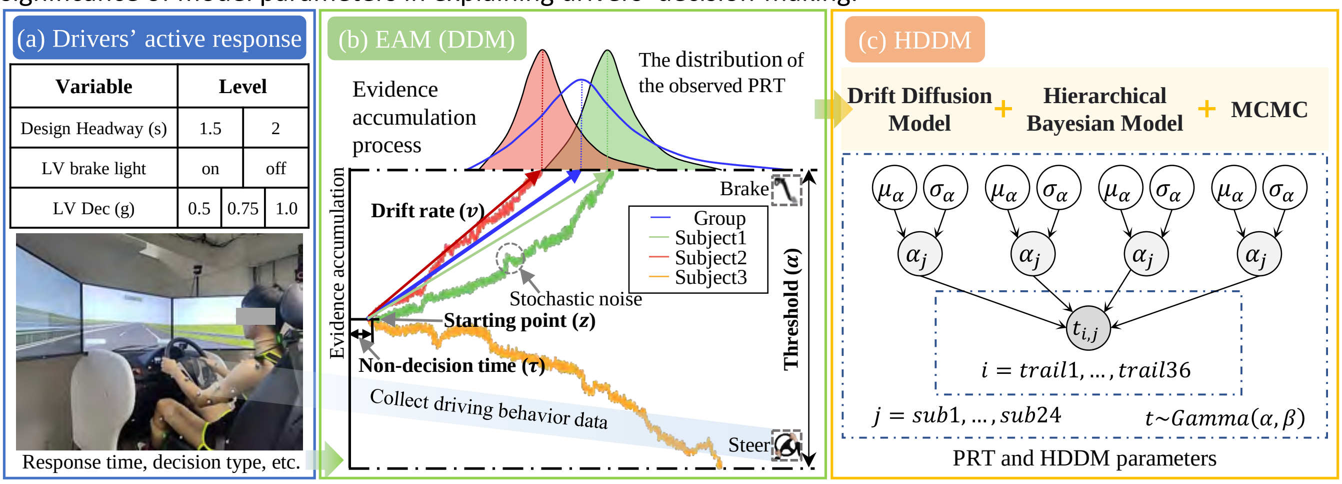

Fig. 1. Drivers' active response acquisition, evidence accumulation model framework and HDDM analysis.

III. INITIAL FINDINGS

The average PRT, decision thresholds, and drift rates for each participant are shown in Fig. 2(a). A consistent

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trend is observed between PRT and decision thresholds, with minimal variability in drift rates among participants. This suggests that drivers process information at a relatively uniform rate in safety-critical scenarios, with variations in PRT primarily related to the decision thresholds. Drivers with higher decision thresholds necessitate more information before coming to a decision, thereby leading to longer PRT. The average non-decision time for drivers was found to be 0.45 s, with minimal variance (0.45 ± 0.04 s). This implies that in safety-critical scenarios, drivers' PRT – comprising perception, decision-making, and execution – averages at least above 0.45 s.

Expanding from the base model (M_{base}), our study incorporated variations in decision thresholds and drift rates based on the time headway (THW) and activation of the lead vehicle's brake lights ($M_{a\sim light}$, $M_{v\sim THW}$, $M_{a\sim light;v\sim THW}$, $M_{a,v\sim ligh\ and\ THW}$). This expansion aimed to investigate how external factors collectively impact the decision-making process. The analysis of results revealed that $M_{a\sim light;v\sim THW}$ exhibited the lowest DIC value (-138), indicating a superior balance between model complexity and data fit, thus performing best in explaining the data. Further examination of the posterior distribution of model parameters in $M_{a\sim light;v\sim THW}$ (Fig. 2(b)) demonstrated distinct drift rates and decision thresholds across different conditions, with no overlap observed. Specifically, the decision threshold exhibited a significant reduction in response to the lead vehicle's brake lights being activated, while the drift rate notably increased as the THW decreased. This observation suggests that factors such as THW, related to safety urgency, predominantly influence the rate of evidence accumulation, while cues like the lead vehicle's brake lights serve to modulate drivers' decision thresholds.

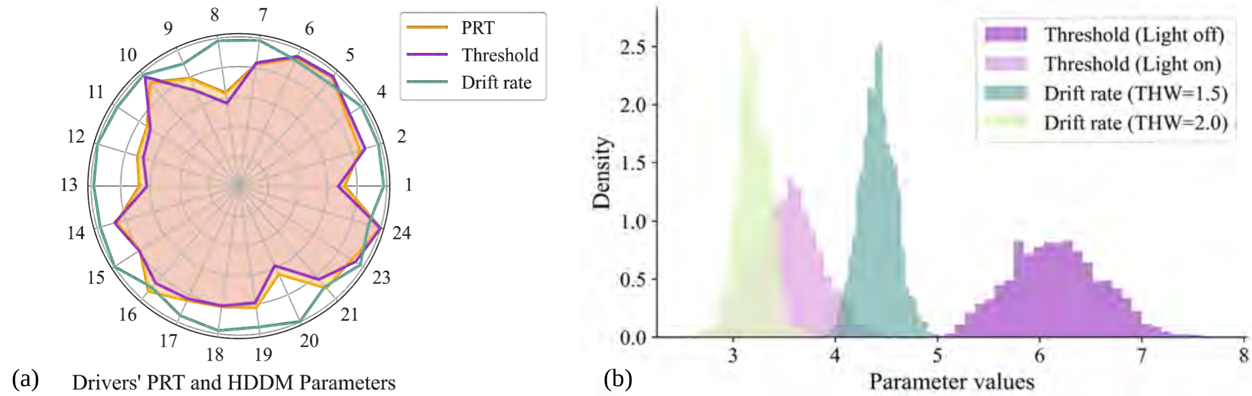

Fig. 2. HDDM model parameters for different participants and scenario variables.

IV. DISCUSSION

Understanding drivers' perceptual decision-making behaviours is pivotal for predicting their responses in safety-critical scenarios, allowing for the adjustment of protection systems to provide optimal safety for humans and reduce the risk of injury. This study employs HDDM to explore the significance and feasibility of evidence accumulation models in elucidating the drivers' perceptual decision-making processes. Model parameters reveal individual differences among drivers, primarily reflected in the varying decision thresholds. Interestingly, drivers' non-decision time in safety-critical situations (0.45 s) offers a crucial reference for determining the minimum PRT. Models that link drift rates to THW and thresholds to the lead vehicle's brake lights show strong fit and interpretability. These findings highlight how scenario variables impact drivers' perceptual decision-making processes: THW influence the rate of evidence accumulation, while the lead vehicle's brake lights modulate drivers' decision thresholds, thereby influencing PRT. HDDM provides insights into how drivers process information, make decisions, and execute actions, thereby enhancing driving safety and achieving optimal protection. Nevertheless, this preliminary investigation only verifies the potential of evidence accumulation models in understanding PRT characteristics and their underlying determinants using a driving simulation dataset of typical safety-critical scenarios. To understand the process comprehensively, further detailed research employing naturalistic driving data is warranted to delve into drivers' evidence accumulation decision-making models. This will not only enable the prediction of driver behaviour and potential injuries but will also guide the development of collision-avoidance algorithms and the implementation of optimal protective measures.

V. ACKNOWLEDGEMENTS

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VI. REFERENCES

[1] David, R., *et al., Front Future Transp*, 2023.
[2] Vanholme, B., *et al., IEEE Trans Intell Transp Syst*, 2013.
[3] Jin, X., *et al.*, *IRCOBI*, 2018.
[4] Ratcliff, R., *et al.*, *Trends Cogn Sci*, 2016.
[5] Pei, X., *et al., IRCOBI*, 2022.