Assessing Driver Decision-Making and Behavior in the Dilemma Zone Across Different Connected Environments: A Driving Simulator Study

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1 INTRODUCTION

The South Korea Traffic Accident Analysis System (TAAS) reported that the number of road traffic accidents causing by intersection violations and red light running (RLR) accounted for 18.23% of the total accidents in 2019-2022, which led to 1,216 fatalities and 238,628 injuries (TAAS, 2023). The rising number of accidents that occur at signal-controlled intersections draws our attention to the safety of driver behavior at approaching intersections. Especially, their hesitation or aggressiveness may cause them slip into dilemma zone during yellow traffic lights. A relatively intensive study of dilemma zones has been conducted this far. Type II dilemma zone, also referred to as "indecisive zone", involve the safety-critical situations where a majority of drivers are confused or challenged to estimate if it is safe to cross or stop (Pawar et al., 2022). Typically, many prior studies reported the time to stop line as a measure to quantify the boundary of the Type II dilemma zone. Overall, the range of TTSL varied among 1-6s (Rahman and Kang, 2021). It is therefore crucial to design various TTSL at onset of yellow light as different critical levels of dilemma zone to evaluate driver performance.
In recently years, the connected vehicle technology (C-V2X) makes safety guidance possible in dilemma zone conditions. While it has proven to provide more low latency and reliable information to connected vehicle (CV), it also presents communication challenges (e.g. time-varying delay and communication interruption, communication loss). Since the latency duration is essentially in the millisecond range that has a negligible effect on the driver (Chen et al., 2020), our study limits in the scope of two impaired communication environments (interruption and loss). The framework of C-V2X technology is shown in figure 1. In perfect communication, the yellow light signal information can be smoothly transmitted as data package forms from initiator (traffic signal) to receiver(vehicle), and then displayed through Argument Reality-Head up Display (AR-HUD). Under communication interruption condition, signal interface or network congestion may cause package loss or damage. The demanding information cannot be transmitted to drivers in seconds would be discard. Further, the transmission channel between two

entities is closed in communication loss conditions, this is due to incomplete coverage of the infrastructure, as up to 80% coverage of V2I capable traffic signal by 2025 (Mashayekh et al., 2014).

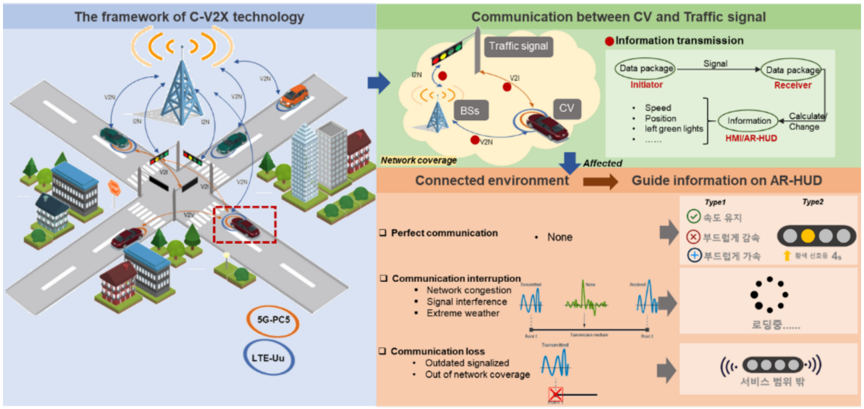

Figure 1 – *The framework of CV2-X technology*

In general, the communication loss or delay has been tested for its effect on safety (Ali et al., 2020). The experimental settings, however, are not compatible with the up-to-date CV2-X technology. There has been little research on how drivers interact with the future possible communication scenarios and during critical events. In order to achieve a more realistic experimental setting, a digital-twin platform combining Unity and VISSIM was developed. Furthermore, a simulator study would be conducted to investigate the effects of various communication environments on the driving performance of drivers in Korea. The driving performance in different communication environments should be compared. Further, the associations between performance indicators and factors such as communication environments, time to stop line, mental workload, and individual characteristics are assessed. The findings would ensure the evolution of CV2X technology can meet future demand as well as improve driving safety.

2 METHODOLOGY

2.1 Digital-twin platform development

Figure 3 displays the digital-twin platform development process. A 4-5 km long road in Daejeon, South Korea was choosing for study. Firstly, a few steps were taken to capture the high-quality basemaps and models: (1) flying a drone to shooting pictures; (2) rendering the maps by iTwin; (3) modeling the buildings with blender. Then, the base map and models were imported to Unity to create virtual-reality scenes. Secondly, the road network should be created in PTV-VISSIM, and the reality trajectories, pedestrians, cyclists can generate in VISSIM. Thirdly, we linked VISSIM and Unity via VISSIM API to implement co-simulation, which enables mutual data exchange. Finally, the built environment can be used for further simulator experiment.

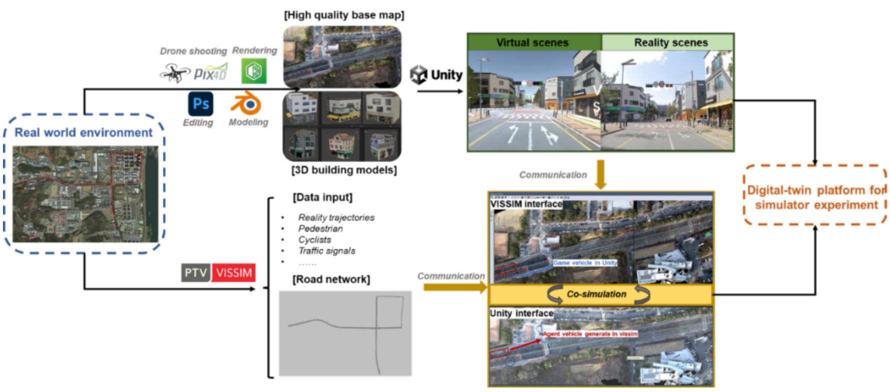

Figure 2 – *Digital twin platform development*

2.2 Experiment design

Figure 3 presents the experiment process. After experiment preparations, 80 drivers are recruited and instructed to participant in the formal experiment. In formal experiment, each participant is informed that they would experience 5 driving trails involving varying information under specific communication environment at yellow traffic light. (1) baseline with no information; (2) perfect communication with a countdown-based guidance, (3) perfect communication with (keep speed/accelerate smoothly/brake smoothly) guidance (the specific instruction would be given by calculating driver's real-time speed and distance to the stop line) (4) communication interruption with loading information, and (5) communication loss with out of service information. The designed icons would show up dynamically in 4s in accordance with yellow lights. The participants should complete all the above 3 trials before the follow two impaired trials to prevent participants from suspecting a system problem. Also, the order among the first 3 trials and between the next two trials should be randomized to avoid a learning effect on the participants. In each trial, 6 yellow light signals were set up at varying time points from the stop line (1s-6s) in one trial to capture the driver's dilemma zone experience approaching an intersection. The other intersections are set to a constant green light and the road's speed limit is 50 km/h.

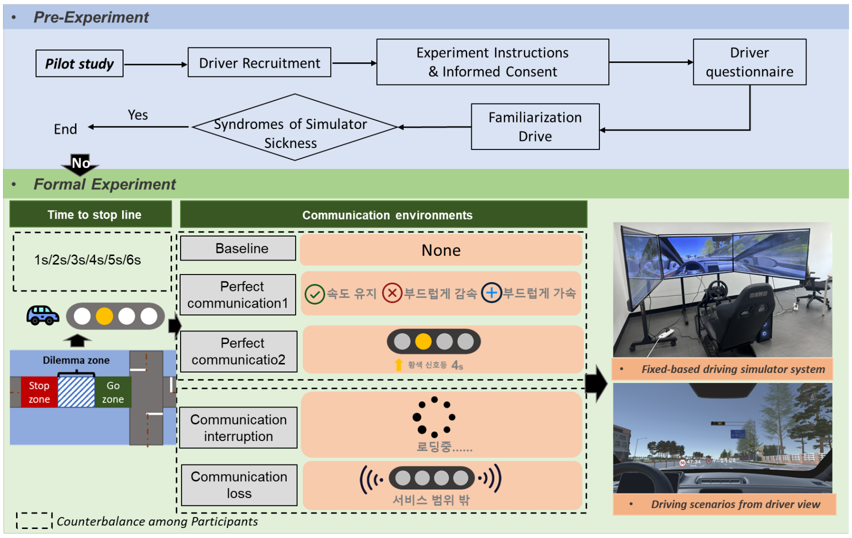

Figure 3 – *Design of the simulator experiment*

3 RESULTS

3.1 Descriptive analysis of driving performance indicators

(*For time limit, we have only collected 4 participants data yet, so the descriptive analysis is displayed here, but the following sections can be hopefully finished before the full paper request date). As shown in table1, the number driver's stop/go decision and average speed during the yellow light period are extracted. Diver's stop and go decision indicated that their decision was more inconsistent when the time to stop line is 2s or 3s. Further, the stop/go decision ratio of drivers varied in different communication environments. The average speed variation is shorter when the time stop line is 2s or 3s in perfect communication environment compared to the baseline condition. Conversely, compared to the baseline condition, the average speed variation is greater in imperfect communication environments in various time to stop line, especially in loading conditions. In the same communication environments, driver shows greater speed variation as their approach time to stop line is 3 or 4s at onset of yellow lights.

Table 1 – *Descriptive analysis of driving performance indicators*

Communication environment	**Time to stop line**					
	1s	*2s*	*3s*	*4s*	*5s*	*6s*
Stop(go) decision						
Basic	0(4)	3(1)	4(0)	3(1)	3(1)	3(1)
Countdown-based instruction	2(2)	2(2)	2(2)	3(1)	4(0)	3(1)
Stop/go instruction	0(4)	2(2)	1(3)	4(0)	4(0)	3(1)
Communication interrupted	1(3)	3(1)	4(0)	4(0)	4(0)	4(0)
Communication loss	1(3)	3(1)	3(1)	4(0)	4(0)	4(0)
Average speed variation (initial to mean)						
Basic	0.14	3.06	3.43	2.64	1.29	1.19
Countdown-based instruction	0.79	2.78	3.30	3.59	2.95	1.89
Stop/go instruction	0.84	2.89	3.34	3.32	2.45	2.39
Communication interrupted	1.81	3.35	4.25	3.29	2.91	2.28
Communication loss	1.90	4.38	2.90	3.53	2.18	2.43

4 DISCUSSION

In current study, driving performance indicators includes speed, lateral controls, stop or go decision are extracted. We would apply the repeated measures ANOVA to compared driving performance various communication environments. In addition, a group random parameters regression model is used to access the association between performance indicators and factors such as communication environments, time to stop line, driver's stop intention of dilemma zone, and individual characteristics.

In this study, we hypothesized that: (1) The perfect communication conditions have positive impacts on drivers' driving behavior in terms of safe and efficiency during the approaching process of signalized intersection. Reversibly, the impaired communication conditions may affect the driving behavior in a negative way. (2) Contributory factors to the driving performance of driver might include communication conditions, time to stop line, driver's stop intention of dilemma zone, driving experience.

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