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A Simulator Study on the Driver Failure and Traffic Conflict in Lane Change Situations on a 2+1 Road

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ABSTRACT

This study examined driver failure and traffic conflict using a driving simulator during lane-change scenarios on a 2+1 road, focusing on differences between day and night conditions. Data on driver failure status and driving behavior were captured through a survey. The study also evaluated driver performance and electrodermal activity. The findings revealed that nighttime lane changes had a shorter minimum time-to-collision (MTTC), indicating a higher traffic conflict severity compared to daytime ($p = 0.046$). It was also found that increased driver stress was correlated with decreased MTTC ($p = 0.039$). Drivers who were prone to making mistakes were closer to collisions ($p = 0.005$), whereas those prone to violations avoided collisions better ($p = 0.027$). Despite facing traffic conflicts, the drivers reported no perception, decision, or planning errors. Moreover, "procedure error" was the most common cause of failure. The study suggests that advanced human-machine interface systems are required to aid perception and decision-making and recommends future research with larger, diverse samples.

CCS CONCEPTS

• **Human-centered computing** → Human computer interaction (HCI); HCI design and evaluation methods.

KEYWORDS

Driver failure, Traffic conflict, Driving simulator, Driver reaction

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1 INTRODUCTION

Driving requires tasks such as perception, decision, planning, and control. Various variables such as the driver, vehicle, and environment influence driving. Drivers may encounter near-accidents, known as traffic conflicts, which involve minimal safety margins [1-2]. Traffic conflicts arise from initial conditions and driver responses [3]. The Swedish Traffic Conflict Technique, which was developed during 1970–1990s, uses video analysis and measures such as time-to-collision (TTC) and speed to evaluate traffic safety [4-5]. Various researchers have used these methods to analyze driver responses [6-7]. Driving simulators have also been used to measure behavior, such as in freeway interchanges [8], automated lane-change assist systems [9], median separation influence [10], hazardous scenario avoidance [11], and cut-in situations [12]. However, little research has focused on cognitive failure preceding driver maneuvers. This study investigated cognitive failure preceding traffic conflicts using a driving simulator to recreate lane-change conflict scenarios. Human-in-the-loop experiments were conducted to observe driver responses in both day and night scenarios and examine their correlation with traffic conflicts. Section 2 describes the simulator environment and methods. Section 3 presents the results and analysis, and Section 4 discusses the findings and conclusions.

2 METHOD

2.1 Driver failure

This study defined driver failure as instances where the driver perceived an error in their thoughts or actions. We adapted Rasmussen's (1982) human error model, which was originally used for plant operators [13]. The following classification was employed. If the driver was unaware of their actions post-event, it was defined as *detection missing*; if the driver's actions did not align with the situation, it was referred to as *identification not correct*; if the goal of the driver's actions was incorrect, it was deemed *goal not acceptable*; if the driver's actions failed to achieve the intended goal, it was *target state inappropriate*; if the intended actions were unsuccessful, it was *task inappropriate*; and if the procedure of the actions was incorrect, it was termed *procedure incorrect*. A failure in any of these categories was categorized as driver failure (Figure 1).

2.2 Traffic conflict induction scenario

The 2+1 road, common in Europe and seen in Germany, Sweden, Ireland, Finland, and Denmark, features a three-lane system with

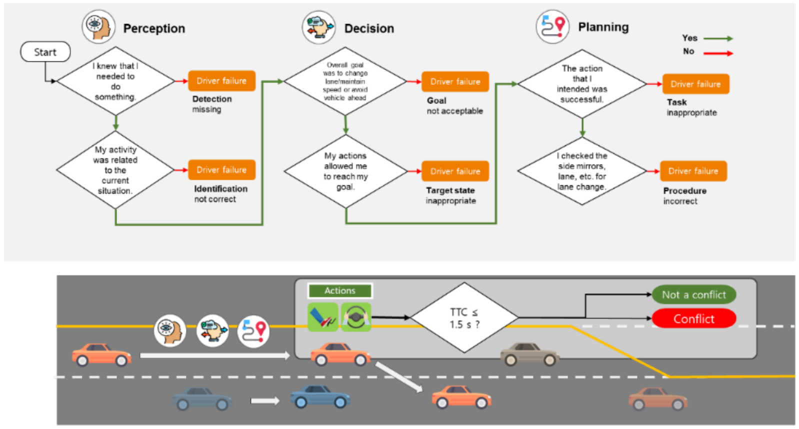

Figure 1: Driver Failure Model

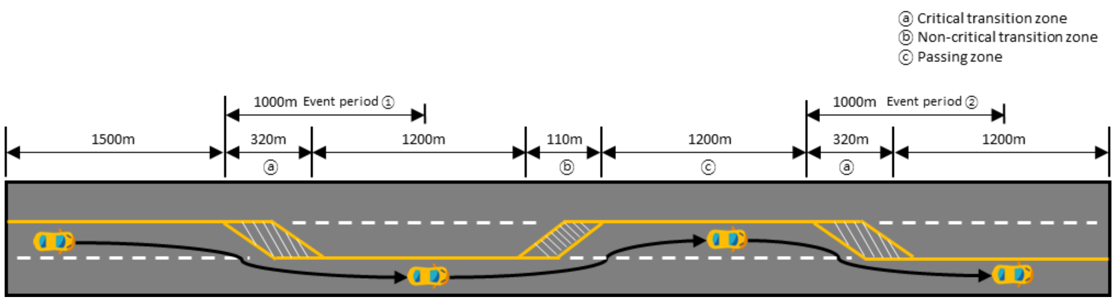

Figure 2: 2+1 Road

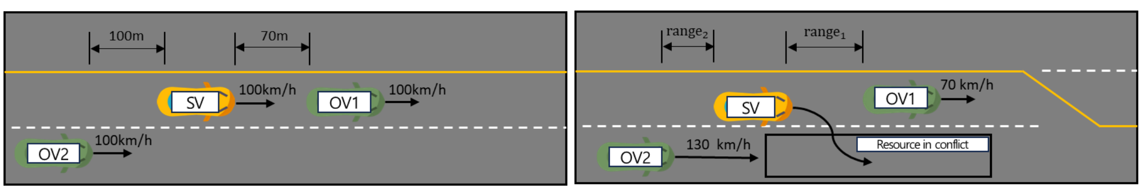

Figure 3: Lane-Change Conflict Scenario

alternating overtaking lanes to ease traffic congestion. It helps maintain traffic flow and reduces costs but may cause driver confusion, collision risks, and overtaking failures. This study created traffic conflict scenarios for a virtual 2+1 road environment (Figure 2), including a lane-change conflict scenario [14-15]. First, the subject vehicle (SV), object vehicle 1 (OV1), and object vehicle 2 (OV2) traveled at 100 km/h. In the event section, OV1 decelerated sharply by 30 km/h in 1 s, and OV2 traveled at 130 km/h. During this time, the driver encountered a traffic conflict, necessitating perception, decision, planning, and control to merge into the lane (Figure 3).

2.3 Apparatus

The data was acquired using a full-cabin-based driving simulator. The display comprises four channels and created an ambiance of realism for the participants through three degrees of freedom: heave, pitch, and roll. Electrodermal activity (EDA) signals were acquired using physiological signals acquisition equipment (BIOPAC MP160). The virtual environment and traffic conditions were implemented using SCANeR ver.2023 (Figure 4).

2.4 Experimental design

2.4.1 Driving environment. In this study, the data was collected during the daytime (12:00 PM) and nighttime (8:30 PM). In addition, a critical transition zone without any events (12:00 PM) was included to observe driver failure in the absence of events and prevent a learning effect among participants. The experiment followed a within-subject design, where each volunteer experienced all conditions. All the conditions and event timings were randomized (Figure 5).

Figure 4: Driving Simulator (Exterior and Interior)

Figure 5: Driving Environment (Day and Night)

2.4.2 Dependent variables. In this study, the driver failure status and driving behavior were evaluated through a survey [15-16]. Driving performance data defined the lane-change time as the period from the onset of OV1 deceleration (event start) to the completion of lane change, the minimum TTC between the SV and OV1 as $MTTC_{OV1}$, and the minimum TTC between the SV and OV2 as $MTTC_{OV2}$. Additionally, changes in the EDA were analyzed by measuring and analyzing the AmpSum and Sum of skin conductance response (SCR) latency for 10 s, from the onset of OV1 deceleration (event start). For detailed explanations of the indicators, please refer to Table 1.

2.5 Experimental protocol

The participants completed an IRB consent form and a demographic survey. Then, they were equipped with an EDA device to monitor physiological signals and perform a practice drive. Once they were familiar with the simulator, they engaged in the main experiment, experiencing three 3.11-minute scenarios. After each scenario, they completed a driver failure survey, with a 2–5-minute break between scenarios.

2.6 Details of volunteers

Six volunteers participated in the experiment. Their average age was 21.83 years (standard deviation (SD) = 1.60 years). The participants had an average driving experience of 19.33 months (SD = 22.50 months). The gender distribution was three females (50%) and three males (50%). The recruitment of participants and the experiment were conducted following IRB approval (code: KMU-202402-HR-396).

3 RESULTS

3.1 Comparison of driver failure and its causes based on time of day

Upon comparing driver failure based on the time of day, three driver failures (50.00%) and three non-failures (50.00%) were observed during the day. At night, there was one driver failure (16.67%) and five non-failures (83.33%). Due to the small sample size, Fisher's exact test, which is appropriate for small datasets, was used. The test showed no statistically significant differences in driver failure occurrence between day and night conditions ($p = 0.545$). Upon analyzing the causes of driver failure, one case of *detection missing* (16.67%), one case of *target state inappropriate* (16.67%), one case

Table 1: Dependent Variables

Category	Dependent variable	Unit	Definition	Ref.
Survey	Occurrence of driver failure	-	Human error occurrence—driver failure did not occur (0), driver failure occurred (1)	[13]
	Driving behavior	points	Driver behavior was assessed using a driving behavior questionnaire (DBQ) with items on *lapse, mistake, and violation* (*lapse*: unintentional actions deviating from the plan, resulting from everyday inattentiveness and unconscious mistakes (8 items); *mistake*: failures in taking correct actions and decisions stemming from a lack of knowledge of road regulations or insufficient driving experience (7 items); *violation*: deliberate disregard for or violation of rules (8 items) (score: *not at all* (0), *very rarely* (1), *occasionally* (2), *frequently* (3), *very frequently* (4), and *almost always* (5)).	[16-17]
Driving performance	Lane-change time	s	The time taken from when OV1 started to decelerate until our vehicle merged into the right lane	[18]
	Minimum time-to-collision ($MTTCov_1$)	s	The minimum time-to-collision between SV and OV1 from the moment OV1 started decelerating to the point when the lane change was completed. $MTTCov_1 = range_1 / v_{OV1}-v_{SV}$	[19]
	Minimum time-to-collision ($MTTC_{OV2}$)	s	The minimum time-to-collision between SV and OV2 from the moment OV1 starts decelerating to the point when the lane change was completed. $MTTCov_2 = range2 / v_{OV2}-v_{SV}$	[19]
	Occurrence of traffic conflict	-	If MTTC was 1.5 s or less, it was classified as a traffic conflict—traffic conflict did not occur (0), traffic conflict occurred (1)	[20]
Physiology	AmpSum	μS	The total amplitude of SCR over 10 s after OV1 deceleration	[21]
	Sum of SCR latency	s	The time from when a stimulus was given to when the skin conductance level began to change over 10 s after OV1 deceleration	[22]

Table 2: Causes of Driver Failure

Time of day	Detection missing	Identificationnot correct	Goalnot acceptable	Target stateinap-propriate	Task inappropriate	Procedure error
Day	1 (16.67%)	0 (0%)	0 (0%)	1 (16.67%)	1 (16.67%)	3 (50.00%)
Night	0 (0%)	0 (0%)	0 (0%)	1 (33.33%)	1 (33.33%)	1 (33.33%)

of *task inappropriate* (16.67%), and three cases of *procedure error* (50.00%) were found during the day. There were no cases of *identification not correct* or *goal not acceptable.* At night, there was one case of *target state inappropriate* (33.33%), one case of *task inappropriate* (33.33%), and one case of *procedure inappropriate* (33.33%). There were no cases of *detection missing*, *identification not correct*, or *goal not acceptable* reported by the participants as causes of driver failure (Table 2).

3.2 Comparison of driving and physiological data based on time of day

The Wilcoxon signed-rank test was employed to compare the paired samples, as it is suitable for small and non-normally distributed datasets. From the results of this test, no significant difference was observed in the occurrence of traffic conflict based on the driving time (p = 1.000). Additionally, there was no significant difference in lane-change time between the day and night conditions (Z = -0.524; p = 0.600). There was also no significant difference in $MTTC_{OV1}$ (Z = -1.572; p = 0.116). However, there was a significant difference in $MTTC_{OV2}$ (Z = -1.992; p = 0.046), with the mean $MTTC_{OV2}$ being 3.28 s (SD = 3.03 s) under the day condition, which was higher than the mean $MTTC_{OV2}$ of 1.38 s under the night condition (SD = 0.54 s) (Figure 6). Furthermore, there was no significant difference in AmpSum (Z = -0.405; p = 0.686) and the sum of SCR latency between the day and night conditions (Z = 0.816; p = 0.414) (Figure 6).

3.3 Correlation Analysis of time-to-collision, driver behavior, and electrodermal activity

This study compared the correlation between $MTTC_{OV1}$, $MTTC_{OV2}$ and DBQ (lapse, mistake, and violation), and AmpSum and Sum of SCR latency. An analysis of the correlation between MTTC and driver and EDA data revealed a significant negative correlation between the DBQ mistake score and MTTCOV1 (r = -0.866; p = 0.005). There was a significant positive correlation between MTTCOV2 and the violation score (r = 0.733; p = 0.039) (Figure 7). There were no significant correlations for the other indicators (Table 3).

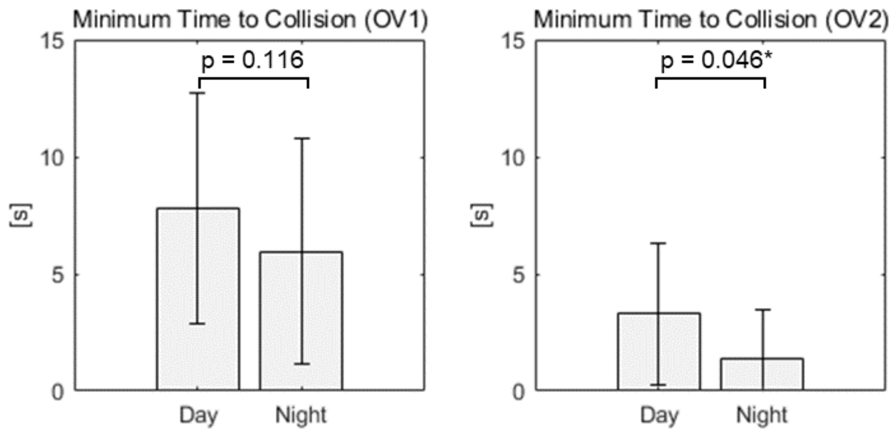

Figure 6: Minimum Time-to-Collision for OV1 and OV2 (Day and Night)

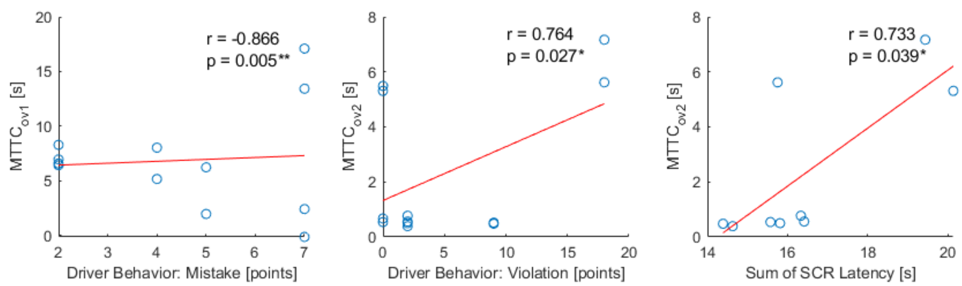

Figure 7: Scatter Plot of Minimum Time-to-Collision with Driver Behavior and Electrodermal Activity

Table 3: Correlation of Minimum Time-to-Collision with Driver Behavior and Electrodermal Activity

DV	Stat.	Driver behavior: lapse	Driver behavior: mistake	Driver behavior: violation	AmpSum	Sum of SCR latency
$MTTC_{OV1}$	r	-0.641	-0.866	0.372	0.016	-0.133
	p	0.087	0.005^{**}	0.364	0.970	0.754
$MTTC_{OV2}$	r	0.695	-0.124	0.764	-0.483	0.733
	p	0.056	0.769	0.027^{*}	0.225	0.039^{*}

3.4 Driver failure and traffic conflict

There were 0 cases where both driver failure and traffic conflict occurred. There were four cases where there was no driver failure, but a traffic conflict occurred. There were four cases where driver failure occurred, but no traffic conflict occurred. Moreover, there were four cases where neither driver failure nor traffic conflict occurred. The Fisher's exact test showed no significant difference between driver failure and traffic conflict ($p = 0.208$) (Table 4).

Table 4: Incidence of Traffic Conflicts by Driver Failure Status

	Traffic conflict	No conflict
Driver failure	0 (0.00%)	4 (33.33%)
Non-failure	4 (33.33%)	4 (33.33%)

4 DISCUSSION AND CONCLUSIONS

This study created lane-change conflict scenarios on a 2+1 road using a driving simulator and collected survey data, driver performance, and EDA from six participants. The results showed no significant differences in driver failure by time of day ($p = 0.545$). During the day, *procedure error* was the main cause, while at night, failures were spread among *target state inappropriate*, *task inappropriate*, and *procedure inappropriate*. This highlights the need for advanced human-machine interface systems to aid perception and decision-making. The $MTTC_{OV2}$ was shorter at night ($p = 0.046$), indicating a higher severity of traffic conflicts. A decrease in the minimum TTC correlated with increased driver stress (p =

0.039). Drivers with higher mistake scores were likely to collide with the vehicle in front (p = 0.005), while those with higher violation scores avoided collisions more effectively (p = 0.027). There was no significant difference in traffic conflict occurrence based on driver failure (p = 0.208), suggesting driver failure may not relate to traffic situations. The study's findings indicate that drivers did not perceive errors without actual collisions and may evaluate their driving positively. Future studies should involve larger samples and consider additional factors such as age and gender, including longitudinal and lateral acceleration and steering deviation.

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