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Preliminary Analysis of Emergency Vehicle Driving Behavior in Traffic Signal Violation Scenarios using a VR Simulator

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Abstract

This paper introduces our investigation into driving behaviors during emergency operations, such as entering an intersection on a red traffic light, to compare and analyze behavior differences based on the driver's emergency driving experience and skills. As a preliminary step, we developed a VR-based simulator that replicates emergency driving scenarios, in consultation with firefighters. Drivers with varied levels of experience and skill in emergency driving executed emergency driving maneuvers using this VR simulator, during which the system recorded their behaviors, including eye movement, head orientation, throttle and brake positions, and steering angle. Our analysis revealed distinct behavioral differences based on experience and skill; for example, professional firefighters repeatedly decelerated, briefly stopped, and checked both left and right sides before entering the intersection.

CCS Concepts

• ***Software and its engineering*** → ***Virtual worlds training simulations;*** • ***Human-centered computing*** → *Virtual reality;*

1. Introduction

Traffic accidents involving ambulances and fire engines during emergency operations have had an immeasurable social impact, including further endangering the patients being transported and the loss of public trust. Although various measures have been taken to prevent such accidents, the increased number of dispatches and the decreased number of skilled first responders have impeded efforts to significantly reduce accident rates. Therefore, various studies have been conducted on the number of ambulance accidents and their characteristics during emergency driving [DGL23, BSM*21, NNM*23, NNM*24, CLW*18, KPK01]. Delavary et al. conducted a literature review of this issue in the United States, Turkey, Taiwan, Canada, France, and Poland [DGL23]. Boldt et al. also studied ambulance accidents in Austria, Germany, and Switzerland [BSM*21], and Norii et al. studied the number of ambulance collisions and their causes in Japan [NNM*23, NNM*24].

A variety of approaches have been taken to ensure greater safety during emergency operations. Norii et al. surveyed the headquarters of fire departments in Japan on the measures taken to prevent ambulance accidents, reporting such initiatives as safe driving training, dash cams, and accident analysis through photos and illustrations [NNM*24]. Albertsson et al. proposed an e-learning tool for insight training of ambulance drivers. They reported that this system could affect drivers' driving behaviors, perceived driving competence, competence to assess risks, self-reflection, and attitudes about safety [AS11]. Prohn et al. proposed and evaluated

Figure 1: *Example of experiment scene with a firefighter*

a simulator-based training approach to knowledge, attitudes, and driving profiles [PH20, PH22]. While these systems seem helpful, they do not deeply capture and analyze detailed human behaviors. Current implementations primarily focus on broad outcomes and assessments, such as changes in attitude or self-reported competencies, rather than moment-to-moment actions and drivers' decisions in emergency driving situations.

Virtual reality (VR) has increasingly been adopted for safety training across various domains in recent years. VR facilitates effective safety education by replicating scenarios that cannot be safely experienced in real environments, such as hazardous conditions at construction sites or during railway maintenance, within

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a controlled virtual space. However, based on our review, no previous study has explored using VR for training in emergency driving scenarios involving ambulances and fire engines.

Previous research has examined games like *Euro Truck Simulator* and *Grand Theft Auto (GTA)*, which simulate long-distance driving and counterterrorism operations [SG24, CSP*20]. In the context of emergency driving, *GTA* does offer opportunities to role-play as emergency medical services (EMS) personnel or firefighters, allowing users to operate emergency vehicles. However, since the game's primary purpose is entertainment, it often encourages behaviors that deviate from realistic driving practices.

Lee et al. employed a VR environment for evaluating autonomous vehicle behaviors and external human-machine interfaces, particularly in signalized and non-signalized intersection scenarios [LYK*23]. The advantages of applying VR to such settings are particularly significant in terms of capturing detailed human behaviors. VR environments allow us to capture participants' precise behaviors, ranging from eye movement and head orientation to specific responses to simulated emergencies. Such detailed data are valuable for understanding the subtleties of human behavior in critical situations, enabling us to train drivers more effectively.

Therefore, this study aims to develop an effective VR-based safety training system specifically for emergency vehicle drivers in emergency driving situations. As the first step toward this goal, our research initially focused on developing a VR driving simulator that enables users to experience emergency driving, specifically targeting the scenario of entering an intersection against a red light. Subsequently, we conducted experiments using the developed VR driving simulator with non-experts and experts (firefighters) to record and compare their driving behaviors during emergencies (Fig.1). The results revealed differences between these types of drivers, such as vehicle speed and their head and gaze motions, thus confirming the divergence in driving behaviors attributable to different experiences and skills in emergency driving. Furthermore, we carried out evaluation experiments by introducing the VR driving simulator to a fire station, where we received positive feedback regarding the immersive VR experience compared to traditional screen-based simulations. These outcomes confirm the effectiveness of using VR in traffic accident prevention training for handling emergency driving scenarios.

2. Implementation of VR Driving Simulator

2.1. System Configuration

The developed VR driving simulator consists of a steering controller and pedals (Logicool G29 DRIVING FORCE) along with a head-mounted display (HMD, VIVE Pro Eye). In addition, Unity (2021.1.7f1) was utilized for software development. The simulator is based on the autonomous driving simulator AWSIM [Tie], which we modified to implement vehicle control software through the steering controller and pedals. We also recorded drivers' behaviors, such as head motions and gaze directions, from the HMD's built-in sensors, as well as the throttle and brake positions, steering angles, and the vehicle's current position (vehicle trajectories).

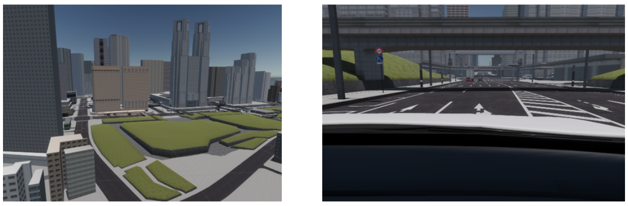

Figure 2: *Experimental environment (left: overall environment; right: driver's perspective)*

Fig. 2 left shows an overview of the VR environment, and Fig. 2 right shows an example scene from the driver's perspective.

2.2. Designing Experimental Scenarios Prone to Accidents

In consultation with two professional firefighters, we investigated situations where accidents involving emergency vehicles are likely to occur, and we selected entering an intersection against a red light as the experimental situation.

A survey of ambulance accidents reported that intersections with red lights and overtaking situations are the most common circumstances of accidents involving ambulances. The literature review also shows the importance of entering an intersection at a red light in preventing accidents that include ambulances and fire engines. However, since previous systems did not analyze detailed human behaviors, it was impossible to highlight specific issues such as insufficient checking to the left and right when entering an intersection.

Based on the above considerations, we targeted the scenario of entering an intersection at a red light (Fig. 3). The simulation included overtaking a car stopped before the intersection and cars emerging from blind spots on the left and right sides. Additionally, the siren sound of an ambulance was implemented to increase immersiveness.

3. Experiment

3.1. Overview

We conducted the following experiment to evaluate whether there are differences in driving behaviors between non-experts and experts (professional firefighters) when entering an intersection against a red light. As discussed in Section 2.2, participants experienced various emergency driving scenarios that included entering an intersection at a red light using the developed VR driving simulator. Their driving behaviors were recorded and compared. The emergency driving scenarios included various patterns, such as the presence of vehicles stopped before entering the intersection and vehicles emerging from blind spots to the left and right. These scenarios were combined in various ways to allow participants to experience a variety of situations.

3.2. Experimental Conditions

In creating scenarios for emergency driving when entering an intersection against a red light, we considered the three elements shown

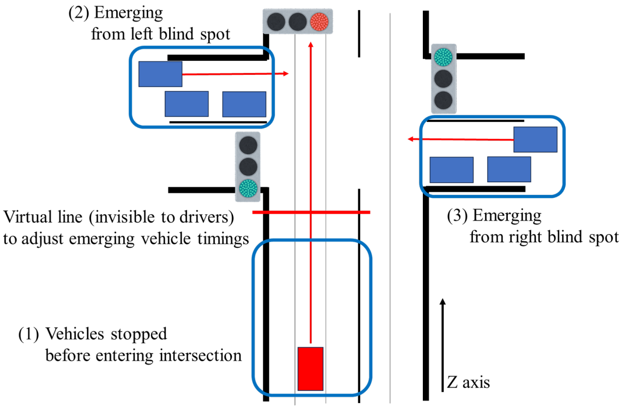

Figure 3: *Experimental conditions*

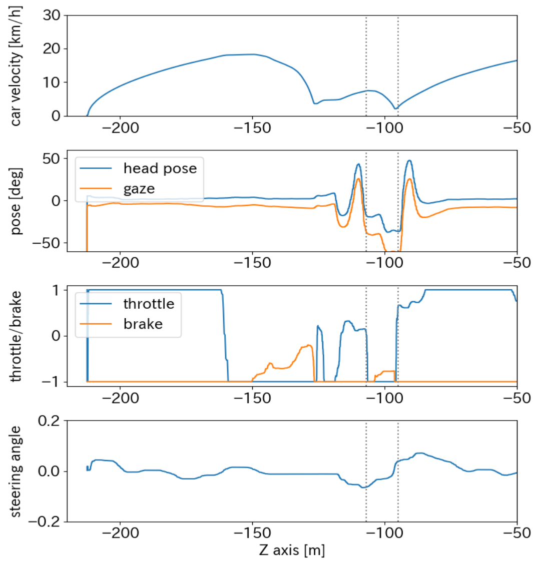

Figure 4: *Example of experimental results (expert)*

in Fig. 3: (1) vehicles stopped before entering the intersection, (2) vehicles emerging from the left, and (3) vehicles emerging from the right. Various scenarios were created by combining these elements. Before entering the intersection, virtual lines (invisible to the driver) were set to adjust the timing of vehicles emerging from the left and right. In this scenario, vehicles emerged into the intersection at a predetermined time after the emergency vehicle operated by the driver (indicated in red in Fig. 3) crossed the virtual line. This timing was designed to increase the likelihood of collisions.

Among the elements composing the scenarios, for (1)—vehicles stopped before entering the intersection—two variations were designed: ① no vehicles were stopped before entering the intersection, and ② a vehicle stopped before entering the intersection (requiring a lane change to overtake it). For (2) and (3)—vehicles emerging from the left and right—three variations were designed: ① a car emerged from a blind spot (movement of the vehicle is visible between stopped cars), ② a car emerged from a blind spot (movement of the vehicle is not visible between stopped cars), ③ no vehicles emerged, and ④ a visible vehicle emerged into the intersection. In this experiment, 16 emergency driving scenarios were created by combining these three types of elements.

3.3. Experimental Procedure

Before the experiment, participants were briefed on its purpose and procedures, and written consent was obtained from the non-expert participants. After wearing the HMD and calibrating its eye-tracking device, they received instructions on basic driving operations. Participants then practiced on a test course to familiarize themselves with the VR driving simulator before proceeding to the actual experiment. After completing the experiment, participants were asked to complete a questionnaire on their driving experience, daily driving patterns, and annual mileage. This questionnaire was designed to collect additional data to provide insights into the participants' driving habits and how these might influence their performance in the VR driving scenarios. The experiment involving non-expert participants was approved by the Institutional Review Board of the Faculty of Engineering, University of Hyogo (No.2021006). The study was conducted with 14 non-expert participants (seven females and seven males, all holding driving licenses) and two expert participants (firefighters). Driving data were collected during the experiment. The non-expert participants underwent experiments for all 16 scenarios described in Section 3.2, while the experts participated in only eight of these scenarios due to time limitations. Fig. 1 shows one of the experts participating in the experiment.

3.4. Results

In the data analysis, the non-expert participants were divided into two groups based on their skills demonstrated in the experiments including the number of accidents: those less skilled at emergency driving (Group 1) and those more skilled (Group 2). Driving behaviors were then compared across three categories: Group 1 (less skilled), Group 2 (more skilled), and experts (professional firefighters). In our comparison of driving behaviors, we focused on a specific scenario in which no vehicle was ahead of the participant's emergency vehicle when entering the intersection, a car emerged from the left, and no car emerged from the right.

Figure 4 shows an example of the obtained driving behaviors of an expert (firefighter) in the experiment. The graphs show the participant's car velocity, head movement and gaze directions (azimuth angles), throttle and brake positions, and steering angles. The horizontal axis represents the vehicle's position in the Z axis shown in Fig. 3. Here, the Z value of the entrance to the intersection is about -110, and that of the center of the intersection is about -95 (indicated by vertical dotted lines).

To facilitate comparisons between the groups, graphs summarizing the vehicle speeds, head movements, and gaze directions for all three groups (typical participants from each group) are presented in Fig. 5. We first focus on a comparison of car velocities across groups. The car velocities of Group 1 (less skilled) were generally higher, while there was no significant difference in car velocities

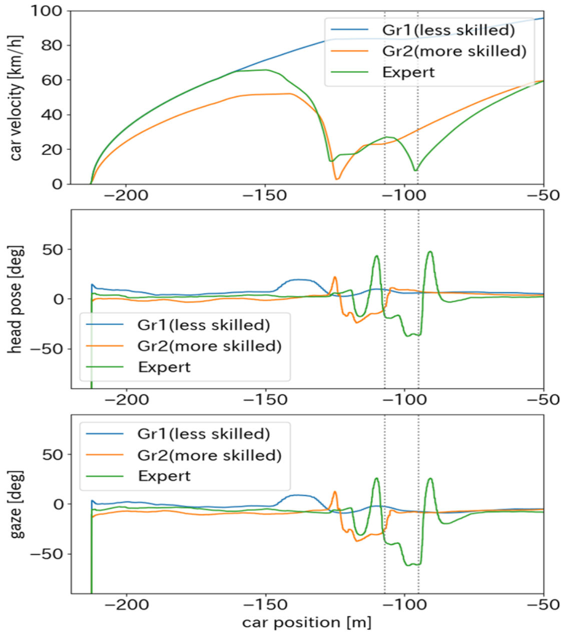

Figure 5: *Comparison of car velocities and head and gaze motions*

between Group 2 (more skilled) and experts. However, although many in Group 2 decelerated and stopped only before entering the intersection, the experts decelerated and stopped before entering the intersection and again just before crossing the center of the intersection.

Comparing head poses and gaze directions reveals that the magnitude of azimuth angles (left and right movements) of the head and gaze was smallest for Group 1 (less skilled) and largest for the experts. Additionally, the timing of checks to the left and right before entering the intersection occurred earlier for Group 1 (less skilled), whereas the experts performed these checks several times, including just before entering the intersection. Taking positive values of the head and gaze movements to indicate the right direction, the analysis of left and right checks shows that Group 1 tended to check only the right direction, i.e., neglecting checks to the left. The experts, on the other hand, checked in the order of left then right, ensuring they checked the right side just before entering the intersection, where the likelihood of encountering a vehicle was higher.

This analysis indicates that the experts decelerated and briefly stopped before entering an intersection, performing thorough left and right checks. Furthermore, they continued this practice of decelerating, stopping, and checking while passing through the intersection. In contrast, Groups 1 (less skilled) and 2 (more skilled) failed to take these precautionary measures while crossing the intersection, with insufficient deceleration, stopping, and checks of the left and right sides.

4. Demonstration Experiment in Fire Station

Following up on the experiment in Section 3, we conducted an evaluation experiment at a fire station, bringing in the VR driving simulator to acquire driving data from many emergency service staff. This evaluation considered feedback from the experts (two firefighters) during the initial experiments, particularly the suggestion that scenarios could be made more challenging by adjusting the timing of emerging vehicles. Nine individuals participated, and their driving behaviors were recorded. Additionally, feedback on the VR driving simulator was collected after the experiment. While a direct comparison with the results of Section 3 is not feasible due to the changed experimental conditions (emerging vehicle timings), we observed similar trends in driving behaviors, such as deceleration, brief stops before and while entering the intersection, and left and right checks.

Feedback from the evaluation highlighted the following points:

- The VR simulator provided a more immersive experience compared to looking at a screen.
- The absence of side mirrors was identified as a drawback.
- Simulating multiple intersections, rather than a single one, was suggested as an improvement.
- Participants expressed interest in testing the system with traffic environments similar to their local area.

In summary, while evaluations of the VR driving simulator for emergency driving revealed several areas for improvement, its immersive experience was well received and positively evaluated by the participants.

5. Conclusion

In this study, we developed a VR driving simulator for emergency driving and recorded driving behaviors while entering traffic intersections against a red light. Experiments were conducted to compare the differences in behaviors among groups with various levels of driving experience and skills. By comparing the driving behaviors of non-experts and experts, we identified variations in driving behaviors based on experience and skill levels.

However, the current analysis was only a qualitative comparison; therefore, we need to conduct quantitative comparisons as well as measuring immersiveness [WS98] and considering motion sickness [GMM*01]. Moreover, considering the feedback received during the experiments, we will continue to improve the VR driving simulator, such as adding side mirrors, creating various emergency vehicle driving situations, and incorporating traffic environments similar to the local area (Himeji City) using 3D models provided by Project Plateau [Pro].

Furthermore, while this paper focused on the stark contrast between professionals and amateurs to determine whether there are behavioral differences among drivers with different levels of skill, the ultimate goal of our research is to evaluate driver skills based on observed driving behaviors. To achieve this, we intend to conduct further experiments to examine subtle differences in driving behaviors among experts with diverse experiences.

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