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Gap Acceptance Behavior of Young Drivers at Signalized Left Turns – A Driving Simulator Study

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Abstract: Intersections are critical points in the road network where numerous traffic conflicts occur, making the study of gap acceptance behavior essential for enhancing traffic safety and efficiency. This study investigates the factors influencing gap acceptance behavior among young drivers (aged 20-30 years) at four-way intersections during permissive left turns. It examines how traffic volume, queue length, and pedestrian crossings affect young drivers' decision-making processes when accepting safe gaps. Twenty young drivers participated in simulated driving scenarios designed to reflect real-world conditions, with various traffic scenarios that varied in volume, queue length, and the presence of pedestrians. Primary data collected included gap acceptance times and physiological responses such as electrodermal activity and heart rate variability. The physiological data revealed significant correlations with gap acceptance behavior. The study showed significant effects of queue length, traffic volume, and pedestrian presence on accepted gap values, while no significant effects were observed on rejected gap values. High traffic volumes and longer queue lengths led to shorter accepted gaps due to increased pressure on drivers. The presence of pedestrians further complicated the decision-making process, often leading to either overly cautious behavior or risky gap acceptance. These findings emphasize the importance of considering environmental and physiological factors in understanding young drivers' gap acceptance behavior, with implications for intersection safety, traffic management, and the development of context-aware autonomous vehicle systems.

Keywords: Gap acceptance behavior, Young drivers, Pedestrian safety, Traffic dynamics, Permissive left-turns, Physiological responses

1. Introduction

Understanding the factors influencing gap acceptance behavior is crucial for improving traffic safety and efficiency at intersections (Shirazi & Morris, 2017). Gap acceptance is the decision-making process that drivers undergo when determining whether it is safe to turn left across oncoming traffic (Pawar & Velaga, 2022). Intersections are complex traffic environments where multiple factors can influence a driver's decision to turn left. Young drivers, in particular, may exhibit different gap acceptance behaviors compared to older drivers due to their varying levels of experience, cognitive processing, and risk perception (Liu et al., 2017; Yan et al., 2007). Traffic volume is a critical factor that affects gap acceptance behavior. High traffic volumes can lead to longer wait times and increased pressure on drivers to accept smaller gaps, potentially leading to unsafe turning decisions (Cooper & Zheng, 2002). Conversely, low traffic volumes may provide more opportunities for safe gap acceptance, but may also lead to overconfidence and riskier driving behaviors (Smiley & Rudin-Brown, 2020). Queue length, or the number of vehicles waiting at the intersection, also plays a significant role in gap acceptance (Zohdy et al., 2010). Queue length is defined as the distance from the stop line to the tail of a single vehicle stopped in a single lane during red light within one signal cycle. For example, one stopped car indicates a queue length of one unit while two stopped cars specify a queue length of two units. Longer queues can increase the time pressure on drivers to accept gaps quickly, while shorter queues may allow for more cautious and deliberate decision-making. Understanding how young drivers navigate these scenarios is essential for developing targeted interventions to improve traffic safety. Pedestrian crossings add another layer of complexity to the decision-making process (Guan et al., 2023). The presence of pedestrians can distract drivers and force them to split their attention between oncoming traffic and pedestrian movements. This can lead to either overly cautious behavior, resulting in increased wait times, or risky decisions if drivers fail to adequately account for pedestrian crossings. Approximately one-third of traffic fatalities occur at intersections, and one-third of these fatalities occur

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at signalized intersections (FHWA, 2024). Left-turn collisions account for about half of the fatalities at signalized intersections (Transport Canada, 2019). Left-turn lanes are used to provide a safe location for left-turning vehicles to wait for a gap in traffic and reduce rear-end collisions (Castellucci et al., 2020). Younger drivers, particularly males, tend to be involved in crashes at intersections due to insufficient experience, speeding, and aggressive driving (Sifrit et al., 2010). These vehicle crashes are the leading cause of death for people aged below 34 (Rahman et al., 2021). Accurately finding the safe time interval to accept a gap at a four-way intersection is more complicated compared to T-junctions. More research is needed to determine how the gap acceptance rate of younger drivers is affected by various factors while making left turns at four-way intersections. One significant factor affecting the gap acceptance rate is traffic flow (Bagheri et al., 2022). High traffic flow increases signal wait times, which can pressure drivers into taking unsafe gaps. Additionally, queue length, i.e., the number of cars waiting to make a left turn, also affects drivers' decisions regarding gap acceptance. Distractions like pedestrians crossing the road also impact the gap acceptance rate, as drivers' focus may shift, leading to deviations in their decision-making while making left turns (Pawar & Velaga, 2022). Therefore, it is important to understand how these factors impact younger drivers' gap acceptance behavior in four-way intersections.

The present study aims to investigate the factors influencing gap acceptance behavior among young drivers (aged 20-30 years) at four-way intersections during permissive left turns. Specifically, this research will examine how traffic volume, queue length, and pedestrian crossings affect the decision-making process in accepting safe gaps. The findings from this research will provide valuable insights for traffic engineers and policymakers to design safer intersection environments and develop targeted educational programs for young drivers.

2. Methodology

2.1 Hypothesis

The study aims to examine the gap acceptance behavior of young drivers aged 20-30 years under various traffic conditions, focusing on four key factors: age, queue length, traffic volume, and the presence of pedestrians. The hypotheses are structured as follows: for age differences in gap acceptance, the null hypothesis (H0) posits that there is no change in the gap accepted values among young drivers aged 20-30 years, while the alternative hypothesis (HA) suggests a change in these values. Regarding queue length, H0 states that there is no significant difference in the mean accepted gap value between different queue lengths, whereas HA proposes a significant difference. For traffic volume, H0 claims no significant difference in the mean accepted gap value between different traffic volumes, contrasted by HA, which indicates a significant difference. Lastly, concerning the presence of pedestrians, H0 asserts that there is no significant difference in the mean accepted gap value in the presence of pedestrians, while HA argues there is a significant difference.

2.2 Participants

The study recruited 20 young participants aged between 20 to 30 years (Mean = 25.95; SD = 1.66). These participants were primarily sourced from the University of Waterloo and neighboring colleges. All participants held a valid Canadian G2 or G Driver's License and were active drivers at the time of the study. Participants had between 1 to 11 years of driving experience since obtaining their first driver's license, with an average of 5.9 years. They were screened using the Trail Making Test (TMT) [67], with a cut-off score of 29 seconds or greater for test A and 75 seconds or more for test B, and a cut-off score of 23 on the MSSQ-Short [66] . Participants with visual acuity poorer than 20/50 in Snellen Near and Far Visual Acuity tests [65, 66], whether with or without corrective lenses, were excluded from the study. Additionally, individuals with known vertigo or motion sickness were deemed ineligible due to their susceptibility to simulator sickness. Each participant was remunerated $15 for their involvement. This study received ethics clearance (ORE #44672) from the University of Waterloo Office of Research Ethics and was conducted in accordance with the approved protocols.

2.3 Apparatus

In this study, driver behavior was evaluated using multiple modalities, including physiological monitoring, eye-tracking, and vehicle kinematics. The experimental drive required participants to follow audio directions and make left turns as instructed. If a participant missed a turn, the vehicle was reset to the previous path, allowing the participant to resume driving from the starting position. The experiment was conducted in a controlled environment with only the participant and the experimenter present. Participants were informed that they could request to stop the experiment at any time, based on their comfort with the equipment and the procedure. We used Carla driving simulator which is an open-source driving simulator that allows for the creation and integration of custom scenarios and maps (Misra et al., 2023). It supports various sensors such as lidar, radar, and cameras, and accommodates different types of road conditions including urban, suburban, and highway environments. This simulator provided a realistic driving environment for participants to navigate and was crucial for assessing their driving behavior in response to various traffic conditions. For eye tracking, Dikablis Glasses 3 was used that features an integrated camera that records video of the user's eyes and surroundings at a resolution of 768x576 pixels and a frequency of 30 Hz. The glasses require a 4-point calibration to accurately track the pupil of the eye. These glasses were used to monitor and analyze participants' eye movements and gaze patterns during the driving tasks. Further, E4 Empatica Wristband (McCarthy et al., 2016) was used to obtain physiological data on electrodermal activity (EDA) and inter-beat interval (IBI). The initial time of the session is recorded in Unix timestamp (UTC). The wristband can connect to any device with a Bluetooth connection and transfer data in real time. The experimental setup has been illustrated in Figure 1.

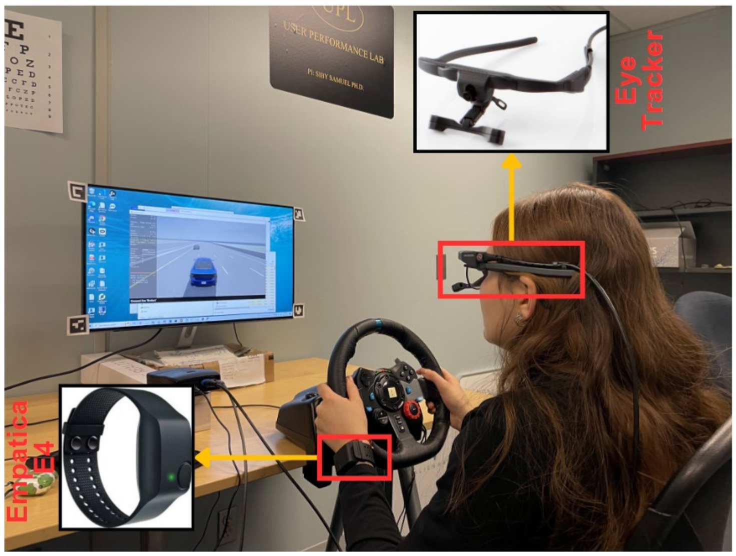

Figure 1. Illustration of the Experimental Setup

2.4 Driving Scenarios

We developed a total 12 simulated scenarios based on four-way permissive intersections, where participants were required to make left turns. Unlike protected left turns, permissive left turns do not have a dedicated left turn arrow or a green light signaling it is safe to turn. Instead, drivers must yield to oncoming traffic and pedestrians before making the left turn. The scenarios varied in traffic volume, queue length, and the presence of pedestrians, all taking place on a four-way lane road with a speed limit of 60 km/hr. One specific scenario involved crossing a two-way lane road. The traffic was scripted in all scenarios, with higher traffic conditions involving 300 vehicles and lower traffic conditions involving 150 vehicles. In higher traffic scenarios, there were more oncoming vehicles, while in lower traffic scenarios, there were fewer oncoming vehicles. Each traffic condition included variations in queue lengths—zero, one, and two queue lengths—and was conducted both with and without pedestrians. Participants followed an audio-guided route throughout each scenario, ensuring consistency in navigation. The gap between the left-turning vehicle and oncoming traffic was measured from the video data. Each scenario was approximately 2 minutes long and designed to challenge the participant's decision-making and gap acceptance behaviors.

2.5 Experimental Design

The experiment employed a mixed factorial design with young drivers. The independent variables included traffic volume (high vs. low), the presence of pedestrians (with vs. without pedestrians), and queue length (zero vs. one vs. two cars). Each participant navigated twelve randomized scenarios, ensuring each scenario was experienced only once. All scenarios were conducted during daytime under controlled conditions with a uniform speed limit of 60 km/h. We examined gap acceptance behavior by measuring both dependent and independent variables. Dependent variables included the time intervals accepted (Accepted Gap) and rejected (Rejected Gap) by drivers when making left turns. Independent variables encompassed various factors influencing gap acceptance, including Traffic Volume (categorized as High or Low), Queue Length (categorized as Zero, One, or Two cars in queue), and Presence of Pedestrians (categorized as With or Without pedestrians). These variables were systematically manipulated across different driving scenarios to investigate their effects on drivers' gap acceptance decisions.

3. Results and Discussion

Younger drivers demonstrated a propensity to accept larger gaps when faced with longer queues, higher traffic volumes, and the absence of pedestrians. For example, at queue length 0, younger drivers accepted gaps ranging from a minimum of 2.05 seconds to a maximum of 4.16 seconds, whereas at queue length 2, the accepted gap time ranged from 2.05 seconds to 5.98 seconds. Similarly, younger drivers accepted longer gaps when traffic volume was higher, with gap acceptance times ranging from 2.19 seconds to 5.98 seconds, compared to lower traffic volume conditions where gap acceptance times ranged from 2.03 seconds to 3.99 seconds. They had a mean accepted gap of 3.312 seconds (SD = 0.908), with a median of 2.99 seconds and a kurtosis of -0.29, indicating a relatively flat distribution and there are no significant outliers. For rejection gap analysis, drivers demonstrated a pattern of rejecting fewer safe gaps compared to their older counterparts, particularly when faced with higher traffic volumes and pedestrian presence. The mean number of rejected gaps was 1.1291 (SD = 1.1625), with a median of 1 and a kurtosis of -0.27, suggesting relatively falt distribution with no significant outliers. It suggests that younger drivers may have a higher tolerance for risk or greater confidence in their gap acceptance abilities compared to older drivers. At higher traffic volumes, younger drivers rejected a maximum of 4 safe gaps, whereas older drivers rejected up to 8 safe gaps. T-Test conducted specifically for younger drivers revealed significant differences in both gap acceptance and rejection behavior compared to older drivers. For the accepted gap values, the P-value was found to be less than 0.05 ($P < 0.05$), indicating a statistically significant difference between the gap acceptance behaviors of younger and older drivers. Similarly, for the rejected gap values, the P-value was also less than 0.05, suggesting a significant disparity in gap rejection tendencies between the two age groups.

Repeated measures ANOVA was conducted to examine the influence of queue length, traffic volume, and pedestrian presence on both accepted and rejected gap values among younger drivers. The analysis revealed significant effects of these factors on the mean accepted gap values among younger drivers, indicating their influence on intersection decision-making processes. The analysis demonstrated a statistically significant difference in mean accepted gap values across different queue lengths, suggesting that queue length significantly influences the gap acceptance behavior of younger drivers. This finding underscores the importance of considering queue dynamics in intersection design and traffic management strategies. Similarly, significant differences in mean accepted gap values were observed between different traffic volumes. This highlights the role of traffic volume in shaping the gap acceptance behavior of younger drivers, with higher volumes potentially leading to more cautious gap acceptance decisions. The presence of pedestrians also had a significant impact on the mean accepted gap values among younger drivers. This suggests that younger drivers may adjust their gap acceptance behavior when pedestrians are present at intersections, emphasizing the importance of pedestrian-friendly infrastructure and safety measures. Significant interaction effects were observed between different independent variables, such as "Traffic: Queue," "Traffic: Pedestrians," and "Queue: Pedestrians." These interactions indicate that the combined influence of multiple factors can further modulate gap acceptance behavior among younger drivers, highlighting the complexity of decision-making processes at intersections. In contrast, the analysis showed no significant differences in rejected gap values between different queue lengths, traffic volumes, and pedestrian presence. This suggests that these factors may not substantially impact the gap rejection behavior of younger drivers. Moreover, no significant interaction effects were observed between independent variables such as "Traffic: Queue," "Traffic: Pedestrians," and "Queue: Pedestrians" (all $p > 0.05$). This indicates that the combined influence of these factors does not significantly modulate gap rejection behavior among younger drivers. Table 1 illustrates the statistical results for both accepted and rejected gap values.

Table 1. ANOVA Results for Accepted and Rejected Gaps Based on Various Variables

Variables	Accepted Gap	Rejected Gap
Traffic	0.000 ($p < 0.05$)	0.840 ($p > 0.05$)
Queue	0.000 ($p < 0.05$)	0.691 ($p > 0.05$)
Pedestrian	0.000 ($p < 0.05$)	0.813 ($p > 0.05$)
Traffic: Queue	0.004 ($p < 0.05$)	0.656 ($p > 0.05$)
Traffic: Pedestrian	0.118 ($p > 0.05$)	0.257 ($p > 0.05$)
Queue: Pedestrian	0.553 ($p > 0.05$)	0.702 ($p > 0.05$)
Traffic: Queue: Pedestrian	0.015 ($p < 0.05$)	0.797 ($p > 0.05$)

To assess the assumption of homoscedasticity, diagnostic plots were generated (see Figure 2). These plots depict the unexplained variance (residuals) across the range of observed data. In the scale-location plot, the red line representing the mean of the residuals is horizontal and centered on zero or near one, indicating the absence of large outliers that could bias the model. Additionally, the normal Q-Q plot, which compares the theoretical residuals of a perfectly homoscedastic model with the actual residuals of the current model, shows minimal deviation. On the other hand, The baseline analysis comparing EDA and HRV values between younger and older drivers revealed no statistically significant differences (EDA: $p = 0.26$, HRV: $p = 0.09$), indicating similar physiological arousal levels across age groups. However, when investigating the relationship between EDA, HRV, and gap acceptance behavior among younger drivers, both variables exhibited a significant impact (EDA: $p < 0.05$, HRV: $p < 0.05$). This suggests that variations in EDA and HRV levels significantly influence gap acceptance behavior among younger drivers, supporting the alternative hypothesis. Specifically, higher or lower EDA and HRV levels appear to correlate with differences in gap acceptance behavior among younger drivers, highlighting the importance of physiological factors in their decision-making process. Furthermore, hypothesis testing using Pearson's r test confirmed a positive correlation between gap acceptance behavior and independent variables such as queue length, traffic volume, and pedestrians for younger drivers. This indicates that these factors play a role in shaping gap acceptance behavior among younger drivers, contributing to a better understanding of their driving decisions. Additionally, the homoscedasticity diagnostic plots for HRV and EDA among younger drivers demonstrated that the model fits the assumption of homoscedasticity (see Figure 2). The plots showed the unexplained variance (residuals) across the range of observed data, with the mean of the residuals centered on zero or near one. This suggests that there are no large outliers that could bias the research model, further validating the findings related to EDA, HRV, and gap acceptance behavior among younger drivers.

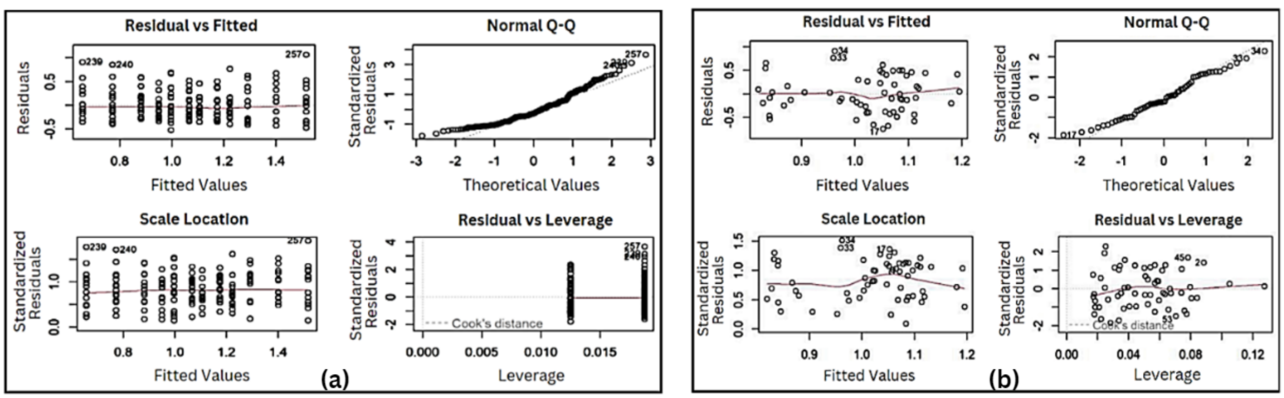

Figure 2: Homoscedasticity Diagnostic for the (a) three variables; and (b) HRV and EDA

In summary, this study on the gap acceptance behavior of younger drivers offers valuable insights that are highly relevant to the development and implementation of autonomous vehicles. By analyzing how younger drivers make decisions at intersections and interact with traffic flow, this research sheds light on key factors influencing gap acceptance behavior, which in turn has significant implications for the advancement of autonomous vehicle technology. The findings of this study can be utilized to develop more accurate behavioral models for autonomous vehicles, enabling them to emulate human-like driving behavior with greater precision and reliability. By incorporating insights into how younger drivers navigate traffic scenarios, autonomous vehicles can enhance their decision-making algorithms to navigate complex situations more effectively, ultimately leading to safer and more efficient interactions on the road. Moreover, these insights can also inform the development of personalized AI-based models that adapt to individual driver behaviors, enhancing the overall intelligence and adaptability of autonomous vehicle systems.

3. Conclusion

In conclusion, the study provides comprehensive insights into the gap acceptance behavior of younger drivers and its implications for intersection safety and traffic management. Younger drivers exhibited a tendency to accept larger gaps under conditions of longer queues, higher traffic volumes, and the absence of pedestrians, indicating adaptive decision-making strategies influenced by traffic dynamics. Significant effects of queue length, traffic volume, and pedestrian presence on gap acceptance behavior underscore the importance of considering these factors in intersection design and traffic control measures. While younger drivers adjusted their gap acceptance behavior based on environmental cues, they demonstrated a consistent pattern of rejecting fewer safe gaps compared to older drivers, suggesting potential differences in risk perception. Repeated measures ANOVA highlighted the significant influence of queue length, traffic volume, and pedestrian presence on gap acceptance decisions among younger drivers, further emphasizing the need for context-aware autonomous vehicle systems. Moreover, the study revealed a significant correlation between physiological arousal levels (measured by EDA and HRV) and gap acceptance behavior, indicating the relevance of incorporating physiological factors into driver modeling frameworks. The findings provide valuable insights for the development of autonomous vehicle algorithms and personalized AI-based models that can adapt to individual driver behaviors and environmental conditions, ultimately contributing to safer and more efficient transportation systems.

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