Study and Analysis of Human Discomfort in Autonomous Vehicles

Haotian Su, *Graduate Student Member, IEEE*, and Yunyi Jia, *Senior Member, IEEE*

***Abstract*—Autonomous vehicles (AVs) are heralding a new era in transportation systems, attracting extensive attention from both academia and industries. Presently, predominant efforts are directed toward enhancing safety and efficiency in AV operations. However, the crucial aspect of human discomfort, integral to the AV user experience and capable of influencing user acceptance and eventual AV deployment, remains relatively understudied. To bridge this gap, this paper delves into the influential factors of human discomfort in AVs through human-in-the-loop studies utilizing a high-fidelity autonomous driving simulator featuring six-degrees-of-freedom motions. The investigation examined the impacts of various significant factors, including AV maneuvers, driving styles, and road types, on human discomfort. Through the application of multivariate analysis of variance and mixed logit modeling techniques, the data was quantitatively analyzed. The findings revealed the relationship between various autonomous driving factors and human discomfort, furnishing invaluable insights for the design of future autonomous vehicles.**

***Index Terms*—Autonomous vehicles (AVs), comfort, human factors, human-autonomous vehicle interaction, simulator-based study.**

I. Introduction

AUTONOMOUS vehicles (AVs) are bringing a new paradigm to our future transportation system. Various merits are promised by AVs, including increased safety, less energy consumption and pollution [1], and increased road capacity [2]. Despite plenty of potential merits introduced by AVs, the promotion of AVs has been faced with obstacles from limited user acceptance [3]. In the J.D. Power 2019 Mobility Confidence Index Study [4], a low overall confidence score of 36 out of 100 was revealed to be the consumers' pessimistic attitude toward AVs. This issue mainly results from three aspects: technical concerns, legal concerns, and user experience concerns [5]. From the technical perspective, the users are unwilling to risk themselves and property security with AVs. From a legal standpoint, the users have concerns about the uncertainty of the legal liability of AVs. From the user experience aspect, AVs' ride experience is not as good as what human passengers expect. With these concerns to be solved, massive efforts have been spent on the safety [6], [7] and efficiency [8] of AVs to improve the technical competence of AVs. Authorities are also stepping forward on legislation related to AVs. However, works are still insufficient on user experience topics, especially human ride comfort studies of AVs.

Research into human ride comfort in traditional human-driven vehicles has been ongoing for an extensive period. Traditional aspects such as vibration [9], noise [10], and thermal comfort [11] have received thorough examination over the past decades. These factors are expected to retain their influence in future interactions between humans and AVs. However, alongside these traditional considerations, new challenges emerge concerning human comfort in AVs due to the loss of control from human drivers [12]. Despite not driving in AVs, humans still have mental expectations regarding AV driving behaviors. Any disparity between these expectations and actual AV performance could engender a distinct form of discomfort beyond traditional factors. Hence, this paper seeks to investigate these novel factors through human-in-the-loop experimental studies.

Recently, several studies have emerged focusing on human comfort factors in AVs. According to the taxonomy proposed in [12], these factors can be broadly categorized into traditional vehicle ergonomics factors, covering comfort considerations from conventional human-driven vehicles introduced in the preceding paragraph, and autonomous driving factors, primarily addressing motion sickness, perceived safety, and natural path planning. While extensive research has been conducted on traditional vehicle ergonomics factors, there is a need for new studies to explore comfort-aware behavioral models, planning algorithms, and human-machine interface (HMI) designs in AVs to address gaps in autonomous driving factors. Domova et al. [13] introduced a qualitative model that describes the relationships between major factors and comfort in AVs. The researchers employed the grounded theory method to thoroughly discuss the influence of environmental, vehicle, and user-related factors on AV comfort. However, further validation of the proposed model through user-involved studies is needed. Strauch et al. [14] observed passengers' preferences for AVs to initiate overtaking maneuvers with a larger clearance to the preceding vehicle, while Bellem et al. [15] investigated passenger preferences for acceleration profiles across various AV maneuvers, revealing a preference for smoother accelerations and early lane change actions. Hartwich et al. [16] conducted a

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The authors are with the Department of Automotive Engineering, Clemson University, Greenville, SC 29607 USA (e-mail: haotias@g.clemson.edu; yunyij@clemson.edu).

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simulator-based study comparing passenger comfort in automated and manual driving, emphasizing the significance of driving style similarity for comfort. A significant age-related variation was noted that younger participants preferred familiar autonomous driving styles, whereas older participants preferred unfamiliar styles. Yan et al. [17] proposed a comfort-aware path-planning method for AVs integrating a vehicle-to-infrastructure system to suggest path adjustments based on pre-allocated road surface information, aiming at enhancing ride quality. These studies provide a glimpse into the ongoing research efforts exploring human comfort in AVs.

Human comfort has been delineated in various ways across different studies. Some studies employ a single-dimensional scale where comfort and discomfort are mutually exclusive [18], [19], while others opt for two independent scales to assess them separately [20], [21]. Among studies employing a single scale, two distinct definitions of comfort emerge: one defines comfort as the absence of discomfort [22], [23], while the other defines it as a state accompanied by additional pleasantness [24], [25]. In this study, we adopt the single-dimensional definition, where comfort is associated with the absence of discomfort. Moreover, our focus lies predominantly on discomfort, as it has a dominant influence over human comfort [26]. Furthermore, this study directs its attention toward passenger discomfort induced by AV behaviors, e.g., vehicular maneuvers, and how the vehicle interacts with its surrounding traffic and environment. By doing so, the findings from this study aim to address the gap in understanding autonomous driving factors related to human discomfort, as highlighted in the preceding paragraph.

Despite existing research on how individual factors affect human comfort in AVs, a comprehensive quantitative study on how various critical AV behaviors influence human discomfort during autonomous driving journeys remains lacking. In our recent work [27], we developed a high-fidelity autonomous driving simulator to investigate the prediction of human discomfort levels in AVs using physiological signals obtained from wearable sensors worn by participants. Building upon this foundation, the present paper conducted a thorough study and analysis based on human-in-the-loop experiments conducted within the simulator. We systematically identified a series of factors closely associated with participants' discomfort. Additionally, we employed a mixed logit model to quantitatively assess the influence of these factors on discomfort levels. The primary contributions of this paper encompass a comprehensive experimental investigation aimed at quantitatively identifying influential factors of human discomfort in AVs, as well as a quantitative examination of their impact. Furthermore, an extensive discussion of our findings offers insights into potential solutions for alleviating discomfort among AV passengers.

II. Material and Methods

A. Participants

A total of 20 participants (15 male, 5 female) participated in the study. The ages of participants ranged from 22 to 38 years ($M = 26.2$ years, $SD = 3.4$). All participants were currently holding valid U.S. driver's licenses. Participants signed a written consent form before taking part in the study. All participants received incentive compensations after completing the experiment.

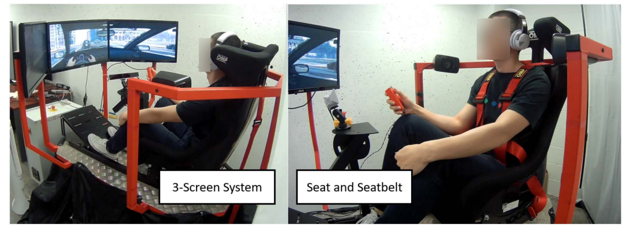


Fig. 1. The driving simulator used in this study.

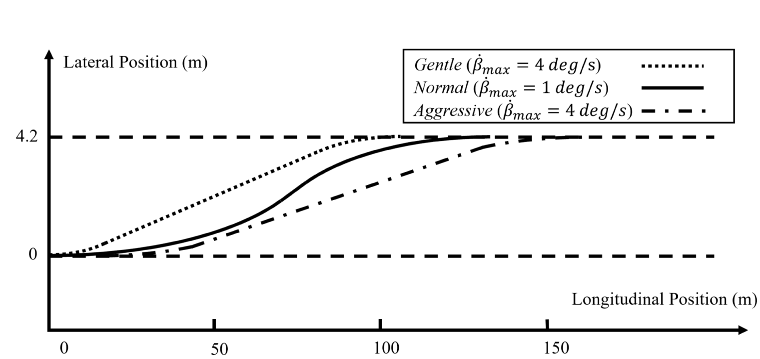
B. Apparatus

A driving simulator that can generate six-degrees-of-freedom (6-DOF) motions was used in the study, as shown in Fig. 1. The simulator is equipped with a multi-media system. By combining motion, visual, and audio stimuli, the simulator can provide an immersive experience for participants. Various driving simulation software is compatible with the simulator setup. The simulator can deliver videos of virtual AV journeys with synchronized vehicle motions as stimuli for participants.

As implied in [28], a set of scaling factors for the lateral and longitudinal motions need to be tuned to generate high-fidelity motions in a driving simulator. During this study's experimental preparation stage, the scales of different motions were calibrated and validated to ensure the motions from the moving platform matched the vehicle motions in the simulation environment. In addition, we also had multiple experimenters take the test riding on the simulator to subjectively perceive the moving platform's motions to make sure they matched well with the stimuli. Combining the visual, audio, and motion stimuli, the system creates a high-fidelity experience of the AV journey for participants.

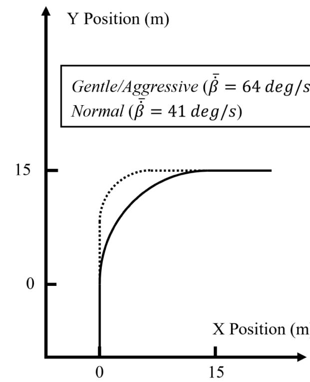
C. Stimuli

A set of pre-recorded AV journey videos with synchronized motions were created as the stimuli in the study. A 3×3×3 experimental design was applied. By combining different routes, types of roads, and driving styles, 27 video stimuli were created. Road types chosen for this study included *City* roads, *Highway* roads, and *Rural* roads. Three different routes were designed for each road type. Driving styles designed for this study included *Gentle*, *Normal*, and *Aggressive* styles. By combining the different routes and driving styles, nine different stimuli were created within one type of road, and 27 stimuli were created for the three types of road selected. Each stimulus consists of the AV completing a journey in one driving style from the start to the destination of a route. The simulated transportation system in the stimuli resembled the natural form, including road network, traffic flows, and traffic rules. Each journey lasts around three to five minutes. The total length of all stimuli summed up is 100 minutes. Three pictures of the video stimuli showing each type of road are displayed in Fig. 3.



(a)

(a) Example trajectories taken from a lane switching maneuver under three different driving styles in a highway journey. The maximal yaw rate $\dot{\beta}_{max}$ values in the trajectories are demonstrated in the legend. Reprinted from [27] with permission. ©2022 IEEE



(b)

(b) Example trajectories taken from a right turn maneuver under three different driving styles in a city journey. The average yaw rate $\bar{\dot{\beta}}$ values in the trajectories are demonstrated in the legend.

Fig. 2. Selected example trajectories of lateral maneuvers under different driving styles in the journeys.

TABLE I
DRIVING BEHAVIORAL CHARACTERISTICS OF THE THREE DRIVING STYLES

Configuration	Driving Style		
	Gentle	*Normal*	*Aggressive*
TCV (*Highway*)	55 mph	70 mph	85 mph
TCV (*City*)	30 mph	35 mph	40 mph
TCV (*Rural*)	30 mph	35 mph	40 mph
OT	Low	Mid	Hi
Number of Overtaking (*Highway*)	2	15	22
LMQ	Hi	Low	Hi
Time Headway (*Highway*)	0.87 s	0.82 s	0.45 s

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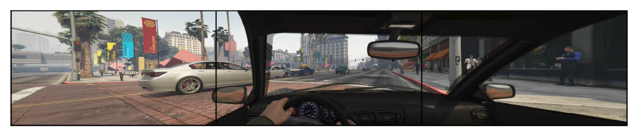
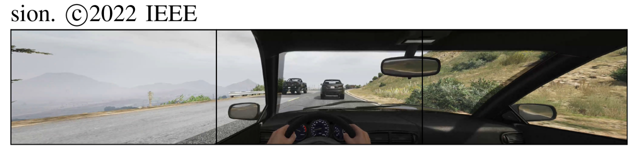


(a) City Road Scenario

(b) Highway Road Scenario. Reprinted from [27] with permission. ©2022 IEEE



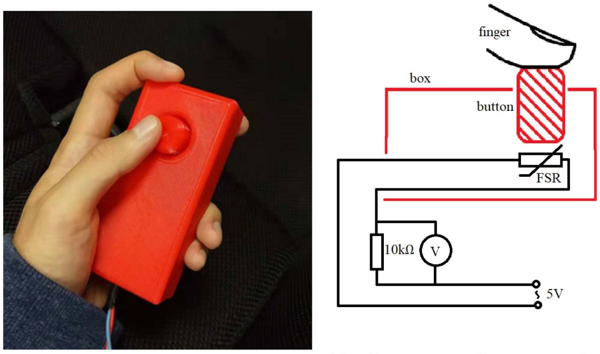
(c) Rural Road Scenario

Fig. 3. Visualization of the video stimuli with notations of monitor setup. The black lines represent the frames of the monitors.

In the stimuli, an SAE Level 5 AV [29] was controlled by an end-to-end controller available from the simulation. The adjustable parameters of the controller were the overall driving style of the vehicle and the cruising velocity limits on different roads, with no onboard sensory data available. Despite the limited sources of data into the controller of the vehicle, several driving behavioral characteristics were recorded from the stimuli to show the differences between various driving styles, including target cruising velocity (TCV), overtaking tendency (OT), lateral maneuvering quickness (LMQ), and time headway (TH). TCV was the target velocity of the vehicle when driving in open conditions without traffic. TCV defined the maximal velocity of the vehicle under a certain driving style and road type. OT was the likelihood of the vehicle overtaking another vehicle when conditions allowed. LMQ described the vehicle's quickness when completing lateral maneuvers, e.g., lane switching and turning at intersections. HT was measured during highway journeys when the vehicle was following another vehicle as the time it took for the vehicle's front end to reach the current position of the leading vehicle's front end. TCV values and OT levels decreased from the *Aggressive* style to the *Normal* style, then to the *Gentle* style. As mentioned, the *Aggressive* and *Gentle* styles had significantly higher LMQ than the *Normal* style. The *Aggressive* style had the shortest HT compared to the other two driving styles with similar values. Detailed information on these behavioral configurations is included in Table I, and several example trajectories of lateral maneuvers are displayed in Fig. 2 to show the differences across driving styles.

D. Data Collection

In this study, discomfort levels were collected using a pressing force collector for the participants to self-report their subjective discomfort levels. Compared to the objective measurements, which usually involve physical or physiological signals [27], [30] to further infer the subjective discomfort levels, the subjective measurement was a more direct indicator of the discomfort levels of participants. The pressing force collector was developed in a pilot study [31] and used in two follow-up studies [23], [27] for real-time subjective data collection. The physical button and the structure diagram of the button are shown in Fig. 4. The pressing force collector consists of a box, a button, and a force-sensitive resistance (FSR). The FSR is placed inside



(a) Picture of the button box. (b) Structure diagram of the button box.

Fig. 4. Subjective discomfort assessment approach using a force pressing device. Reprinted from [27] with permission. ©2022 IEEE

the box with the button above it. When participants push the button, the resistance of the FSR will drop, and the force can be computed according to the conductance map.

In this study, participants were instructed to release the button when there was no discomfort feeling and press the button harder when they perceived a higher level of discomfort. The button was expected to collect the real-time subjective discomfort levels of participants. Participants needed to press the button whenever feeling uncomfortable during a ride and adjust the pressing force according to their feelings. The button should not be released until the discomfort disappears. The amplitudes of the pressing force applied to the button, originally in the unit of Newton, were standardized for each participant across the three experimental sections with the Z-Score methodology to eliminate the individual differences [32]. The standardization process is described by:

$$\mathbf{DLR}_p = (\mathbf{F}_p - \mu_p)/\sigma_p \tag{1}$$

where $\mathbf{DLR}_p$ is the vector that contains the discomfort level rating (DLR) values of participant p during all experimental journeys, $\mathbf{F}_p$ is the vector that contains the raw pressing force values in Newton collected from participant p during the experiment, μ_p is the mean pressing force value, and σ_p is the standard deviation of the pressing force. DLR is a dimensionless quantity and is used to represent the standardized discomfort levels of participants during the experiment.

E. Experimental Procedures

Before the experiment, the participant was required to complete a consent form containing a brief introduction to the study's topic and content. Potential risks of the experiment were also introduced in the form. After the consent form was signed, the participant received a more detailed introduction about the experiment, including devices used in the study, precautions for using the devices, the topic discussed in the study, stimuli they would go through, and instructions on using the pressing button collector. Because the vehicle was an SAE L5 AV, the participant was in the perspective of a passenger in the vehicle, and the only task for the participant during each video stimulus was to report

TABLE II
ARRANGEMENT OF DIFFERENT ROAD TYPES AND DRIVING STYLES IN THE THREE EXPERIMENTAL SECTIONS

	# Section		
	1	2	3
Road Type	*Highway*	*City*	*Rural*
1^{st} Driving Style	*Gentle*	*Normal*	*Aggressive*
2^{nd} Driving Style	*Normal*	*Aggressive*	*Gentle*
3^{rd} Driving Style	*Aggressive*	*Gentle*	*Normal*

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the perceived discomfort level with the pressing button. Before the experiment started, the participant played with the pressing button with visual feedback on how hard the press was. This procedure acted as a learning process for the participant to get familiar with the device before the actual data collection.

Because the dynamics and motions generated by the simulator could not perfectly match the video stimuli, which is a common limitation for all simulator-based studies, motion sickness was a potential risk in this experiment. A questionnaire proposed in [33] was used to monitor the participant's motion sickness. If there was no signs of motion sickness, the experimenter should introduce the next stimulus and start it according to the designed operation flow.

Considering the length of all stimuli, we divided the experiment into three sections and scheduled them on three separate days to avoid excessive fatigue for participants. Nine stimuli of the same type of road were included within each section. The total length of one experimental section was around an hour, including more than 30 minutes of simulator rides and the time consumed during the preparation and breaks during the experiment. The consent form was only signed at the beginning of the first section of the experiment. At the beginning of the follow-up sections, the experimenter only gave the necessary instructions on the experiment. The orders for the road types in different experimental sections and driving styles within each experimental section are displayed in Table II.

We designed the road type selection and driving style order in the first section to help the participant familiarize themselves with the experimental stimuli and develop a criterion for comfort and discomfort. For the road type selection, the *Highway* road type's traffic environment was the simplest among all road types included in the experiment. Starting with the *Highway* would help the participant familiarize themself with the simulator's virtual experience. The *Gentle* style was selected as the first driving style for the same consideration that it could prepare the participant for the simulation experience. The driving style gradually shifted to an overall intermediate style, the *Normal* style, then to the *Aggressive* style. The participant gradually experienced various behaviors of the vehicle and established a criterion for discomfort when riding in an AV.

For the two sections followed, the road type selection and order for driving styles were randomly generated because we assumed the participant adapted to the virtual experience and developed a criterion for comfort and discomfort. The only rule to obey was that the journeys under the same driving style were experienced in a row by the participant. Such an arrangement was intended to avoid confusion about details of the driving styles if the driving style changed frequently. All participants shared the same order of experimental journeys for easy data processing.

F. Data Analysis

A series of vehicular maneuvers in the stimuli were identified first. Discomfort levels of participants were analyzed within each type of vehicular maneuver. Four types of maneuvers were found in all three road types, which were *Acceleration*, *Deceleration*, *Open Driving*, and *Following*. *Acceleration* referred to the vehicle gaining velocity under certain circumstances, e.g., a traffic light turning green, overtaking another vehicle. *Deceleration* typically occurred when the vehicle had to reduce speed due to a traffic light turning red or matching the speed of a slower vehicle ahead. *Open Driving* represented the state of the vehicle cruising with no closely leading vehicle. *Following* referred to the vehicle following another vehicle in the same lane closely.

In addition to the four maneuvers that occurred on all types of roads, there were some road-type-specific maneuvers. *Lane Switch Left* and *Lane Switch Right* were specific to city and highway road types, representing the scenarios when the vehicle changed to the lane on the left or the right. Rural road journeys were completed primarily on two-lane roads with no chance of making a lane switch. *Turn Left* and *Turn Right* were specific to city and rural road types, referring to the vehicle turning left or right at an intersection.

Based on the DLR value gathered during the experiment, a descriptive analysis was performed to obtain an overview of the data. Then, the effects of vehicular maneuvers, driving styles, and road types on DLR values were analyzed using a multivariate analysis of variance (MANOVA). In addition to the MANOVA on the three primary factors, DLR in several driving scenarios was also analyzed in detail.

The use of MANOVA was determined based on the multivariate nature of the data. Each participant generated more than 40,000 data points in the dataset, producing repeated measures within each combination of experimental conditions, i.e., the combination of maneuver type, driving style, and road type. The repeated measures of discomfort levels make the analysis of the data a multivariate analysis. ANOVA is inherently a univariate statistical model. The revised version of the univariate ANOVA for the multivariate situation, the repeated measures ANOVA, is strictly restricted to the sphericity assumption on the data, which is almost always violated [34]. Given the multivariate nature of our data, it is natural to use the multivariate ANOVA, i.e., the MANOVA, to analyze the data. Therefore, instead of using the adapted univariate version of ANOVA, i.e., the repeated measures ANOVA, which is very likely to be statistically flawed due to violating the sphericity of data, using the MANOVA for the analysis in this study is the proper way.

At last, for a deeper quantitative analysis, a mixed logit model was fitted with vehicular maneuver, driving style, and road type as predictors and discomfort level as the outcome. Discomfort levels were categorized into *no discomfort* and *discomfort* based on the distribution of DLR values. The mixed logit model was also chosen because of the repeated-measures design. A fixed effect logit model is built on the assumption that the error term in the model is independent and identically distributed (IID). However, each participant provided multiple responses with correlated error terms, which violated the IID assumption. The mixed logit model uses random effects, by using a random distribution instead of a value as the coefficient for an independent variable, to overcome the violation of IID.

III. Results

A. Descriptive Statistics

Table III contains the descriptive statistics of DLR value in different vehicular maneuvers under various driving styles and road types. The DLR values were aggregated across all participants in the descriptive analysis. Because the DLR value was captured at the sampling rate of 10 Hz, N/10 can be roughly taken as the total duration of each maneuver in seconds. The data contained 43,985 samples in total, therefore it can be roughly taken as that each participant generated more than 4,000 seconds of data. *Open Driving* was the most frequently occurred maneuver in all three road types, with 3,212 samples in *City* journeys, 9,207 samples in *Highway* journeys, and 11,080 samples in *Rural* journeys. *Following* was the second most frequently occurred maneuver in *Highway* journeys ($N = 3,600$) and *Rural* journeys ($N = 4,696$). Whereas *Deceleration* was the second most frequently occurred maneuver in *City* journeys ($N = 1,833$). From the table, we can find that in *City* journeys, there were three maneuvers ending up with DLR values of. 15 or higher, including *Lane Switch Left*, *Lane Switch Right*, and *Turn Right*. In *Highway* journeys, there were two maneuvers with DLR values of. 15 or higher, which were *Following* and *Lane Switch Right*, with *Following* ending up with an DLR of. 279. Excluding maneuvers with less than 100 samples, one maneuver, *Following*, was found to have DLR values of. 15 or higher in *Rural* journeys. The vehicle control strategies for these high DLR maneuvers deserve extra attention to optimize the riding experience.

B. Analysis of Effects of Vehicular Maneuvers, Driving Styles, and Road Types on Discomfort Levels

A three-way MANOVA was conducted to further investigate DLR values as the vehicular maneuver, driving style, and road type variate. In the MANOVA, DLR value was the dependent variable, and vehicular maneuver, driving style, and road type were the independent variables. Levene's test of equality of error variances was performed, and a violation of the assumption of equal variance was found ($p < .001$). Therefore, Pillai's Trace was used for reporting the multivariate test results. The MANOVA results, shown in Table IV, revealed that:

a) there was a statistically significant main effect for vehicular maneuver on DLR value ($F(140, 307363) = 94.1$, $p < .001$);
b) there was a statistically significant main effect for driving style on DLR value ($F(40, 87808) = 225.5, p < .001$);

TABLE III
DESCRIPTIVE STATISTICS (AGGREGATED) OF DLR VALUES IN MANEUVERS UNDER DIFFERENT DRIVING STYLES AND ROAD TYPES

	Driving Style									Overall		
	Gentle			*Normal*			*Aggressive*					
	M	SD	N	M	SD	N	M	SD	N	M	SD	N
City Journeys												
Acceleration	.063	.056	146	.049	.044	551	.145	.141	377	.085	.101	1074
Deceleration	.110	.113	656	.067	.098	559	.228	.150	618	.137	.140	1833
Open Driving	.104	.067	1526	.055	.052	1115	.116	.087	571	.089	.071	3212
Following	.233	.118	309	.039	.021	68	.169	.079	355	.184	.109	732
Lane Switch Left	.207	.134	197	.045	.042	153	.271	.266	135	.174	.189	485
Lane Switch Right	.274	.222	167	.059	.034	166	.259	.165	161	.197	.188	494
Turn Left	.171	.099	297	.044	.034	301	.175	.108	323	.131	.106	921
Turn Right	.189	.151	204	.071	.055	252	.305	.205	231	.185	.178	687
Highway Journeys												
Acceleration	.119	.159	149	.034	.047	969	.143	.109	218	.062	.091	1336
Deceleration	.105	.120	100	.013	.028	164	.134	.164	98	.071	.120	362
Open Driving	.145	.098	4063	.033	.036	2679	.099	.092	2285	.100	.095	9027
Following	.309	.153	1820	.058	.079	504	.325	.118	1276	.279	.160	3600
Lane Switch Left	.129	.128	239	.053	.095	412	.195	.146	442	.127	.140	1093
Lane Switch Right	.284	.103	184	.093	.107	255	.234	.179	357	.200	.162	796
Rural Journeys												
Acceleration	.123	.082	261	.048	.068	407	.111	.084	333	.089	.084	1001
Deceleration	.144	.221	229	.027	.044	359	.230	.207	155	.106	.178	743
Open Driving	.089	.062	4951	.049	.048	4185	.063	.069	1944	.069	.061	11080
Following	.241	.225	1031	.152	.081	1319	.280	.162	2346	.235	.170	4696
Lane Switch Right	.348	.121	29	.003	.008	34	.196	.185	29	.173	.189	92
Turn Left	.146	.096	123	.076	.061	178	.085	.061	111	.100	.079	412
Turn Right	.121	.101	129	.105	.088	111	.106	.045	69	.112	.087	309

TABLE IV
MULTIVARIATE TESTS RESULTS OF THE MANOVA

Effect	Pillai's Trace	*F*	*df*	Error *df*
(Intercept)	0.403	1483.4	20	43903
vehicular maneuver	0.288	94.1	140	307363
driving style	0.186	225.5	40	87808
road type	0.216	266.0	40	87808
vehicular maneuver * driving style	0.307	49.3	280	614824
vehicular maneuver * road type	0.336	69.1	220	483043
driving style * road type	0.214	124.1	80	175624
vehicular maneuver * driving style * road type	0.438	44.7	440	878440

All tests were at the significance level of $p < .001$.

c) there was a statistically significant main effect for road type on DLR value ($F(40, 87808) = 266.0, p < .001$);
d) there was a statistically significant interaction between the effects of vehicular maneuver and driving style on DLR value ($F(280, 614824) = 49.3, p < .001$);
e) there was a statistically significant interaction between the effects of vehicular maneuver and road type on DLR value ($F(220, 483043) = 69.1, p < .001$);
f) there was a statistically significant interaction between the effects of driving style and road type on DLR value ($F(80, 175624) = 124.1, p < .001$);
g) there was a statistically significant interaction between the effects of all three independent variables on DLR value ($F(440, 878440) = 44.7, p < .001$).

C. Right-Heading and Left-Heading Maneuvers

In Table III, it can be observed that right-heading maneuvers yielded higher DLR values than left-heading maneuvers in general, e.g., *Lane Switch Right* in highway journeys (M =. 200) was overall more uncomfortable than *Lane Switch Left* (M =. 127), and *Turn Right* in city journeys (M =. 185) was overall more uncomfortable than *Turn Left* (M =. 131). Post hoc tests were performed to further confirm the statistical significance of the observed differences. Given the imbalanced number of observations under each condition, Scheffé tests were performed to compare the univariate effects between left- and right-heading lane switching and turning maneuvers. Results are summarized in Table V.

TABLE V
SCHEFFE POST HOC TEST RESULTS OF UNIVARIATE EFFECTS COMPARISON BETWEEN LEFT- AND RIGHT-HEADING MANEUVERS

Participant	Mean	Standard Error	95% Confidence Lower Bound	95% Confidence Upper Bound
Lane Switch Right - Lane Switch Left				
P1[ns]	-.005	.011	-.045	.034
P2	-.036	.004	-.052	-.019
P3	.183	.011	.142	.224
P4[ns]	-.012	.010	-.048	.025
P5	.068	.011	.027	.109
P6[ns]	.036	.010	-.002	.075
P7	.039	.008	.009	.069
P8	.194	.011	.153	.235
P9[ns]	.010	.003	-.001	.021
P10[ns]	.002	.008	-.027	.031
P11	.044	.005	.024	.064
P12	.043	.007	.018	.067
P13	.090	.009	.056	.123
P14[ns]	.033	.013	-.014	.080
P15[ns]	.031	.009	-.003	.065
P16	.012	.002	.004	.020
P17	.126	.015	.069	.183
P18	.103	.009	.070	.135
P19	.169	.011	.127	.212
P20[ns]	-.011	.012	-.056	.033
Turn Right - Turn Left				
P1	.065	.012	.020	.110
P2	.039	.005	.021	.058
P3	-.076	.012	-.122	-.029
P4	.049	.011	.007	.090
P5	.062	.012	.015	.108
P6[ns]	-.021	.012	-.065	.023
P7[ns]	.021	.009	-.013	.056
P8	.108	.012	.061	.155
P9[ns]	.005	.003	-.008	.017
P10[ns]	.014	.009	-.019	.047
P11	.095	.006	.071	.118
P12[ns]	.020	.007	-.008	.048
P13	.143	.010	.105	.180
P14[ns]	.049	.014	-.004	.103
P15	.046	.010	.008	.085
P16[ns]	.007	.003	-.002	.017
P17[ns]	.047	.017	-.018	.112
P18[ns]	-.005	.010	-.041	.032
P19	.103	.013	.055	.152
P20[ns]	.046	.013	-.005	.096

[ns] Not significant at the level of $p < .05$.
All other comparisons were at the significance level of $p < .01$.

Twelve participants reported significantly different DLR values in *Lane Switch Right* and *Lane Switch Left* maneuvers. Within these 12 participants, 11 experienced higher discomfort levels in *Lane Switch Right* than in *Lane Switch Left*. For turning maneuvers, 10 participants reported significantly different DLR values in *Turn Right* and *Turn Left* maneuvers. Among the 10 participants, nine reported higher discomfort levels in *Turn Right* than in *Turn Left*. These results indicated that right-heading maneuvers were generating higher discomfort levels than left-heading maneuvers in this study.

TABLE VI
PAIRWISE COMPARISON OF ESTIMATED MARGINAL MEANS BETWEEN *LATERAL MANEUVERS* AND *LONGITUDINAL MANEUVERS*

Participant	Mean	Standard Error	95% Confidence Lower Bound	95% Confidence Upper Bound
lateral maneuvers - longitudinal maneuvers				
P1	0.020	0.005	0.010	0.029
P2	0.007	0.002	0.003	0.011
P3	0.025	0.006	0.013	0.036
P4	0.045	0.005	0.036	0.054
P5	0.038	0.005	0.027	0.048
P6	0.145	0.005	0.136	0.155
P7	0.067	0.004	0.058	0.075
P8	0.036	0.005	0.025	0.047
P9	-0.003	0.001	-0.005	0.000
P10	-0.028	0.004	-0.036	-0.020
P11	0.045	0.003	0.040	0.050
P12	0.016	0.003	0.010	0.022
P13	0.039	0.004	0.031	0.047
P14	-0.125	0.007	-0.137	-0.112
P15	0.017	0.005	0.008	0.026
P16[ns]	0.001	0.001	-0.001	0.003
P17	-0.051	0.007	-0.065	-0.037
P18	0.064	0.004	0.056	0.072
P19	0.069	0.005	0.059	0.079
P20	0.035	0.006	0.024	0.046

[ns] Not significant at the level of $p < .05$.
All other comparisons were at the significance level of $p < .05$.

D. Lateral and Longitudinal Maneuvers

The maneuvers discussed in this study can be roughly sorted into two classes: longitudinal and lateral maneuvers. The longitudinal maneuvers include *Acceleration*, *Deceleration*, *Open Driving*, and *Following*. The lateral maneuvers include *Lane Switch Left*, *Lane Switch Right*, *Turn Left*, and *Turn Right*. Table III suggests that participants endured more discomfort in lateral maneuvers in general.

A new independent variable with two levels, *longitudinal* and *lateral*, was generated as the maneuver type. A three-way MANOVA similar to the model in Section III-B was conducted with vehicular maneuver replaced by maneuver type. The focus is on the main effect of maneuver type, therefore other results from the MANOVA are omitted. The MANOVA results indicated that there was a statistically significant main effect for maneuver type on DLR value ($F(20, 43948) = 127.6$, $p < .001$). Estimated marginal means of DLR values in *lateral* and *longitudinal maneuvers* were compared for each participant. Among the 20 participants, 15 participants experienced significantly higher discomfort levels in *lateral maneuvers* than in *longitudinal maneuvers*. In summary, although the lateral maneuvers ($N = 5,289$) took a much shorter duration in the journeys than the longitudinal maneuvers ($N = 38,696$), they contributed a lot to the discomfort of participants.

E. Interactions Between Ego Vehicle and Other Road Users

There were many scenarios within the journeys where interactions between the ego vehicle and other transportation agents occurred. Discomfort feelings were frequently found in

TABLE VII
SCHEFFE POST HOC TEST RESULTS OF UNIVARIATE EFFECTS COMPARISON BETWEEN *FOLLOWING* AND *OPEN DRIVING*

Participant	Mean	Standard Error	95% Confidence	
			Lower Bound	Upper Bound
Following - Open Driving				
P1[ns]	.004	.004	-.009	.018
P2	.031	.001	.026	.037
P3	.471	.004	.457	.484
P4	.160	.003	.147	.172
P5	.313	.004	.299	.327
P6	.058	.003	.045	.071
P7	.277	.003	.267	.287
P8	.316	.004	.303	.330
P9[ns]	.003	.001	.000	.007
P10	.342	.003	.332	.352
P11	.041	.002	.035	.048
P12	.045	.002	.037	.053
P13	.027	.003	.015	.038
P14	.369	.004	.353	.385
P15	.295	.003	.283	.306
P16	.015	.001	.012	.018
P17	.229	.005	.210	.248
P18	.136	.003	.125	.147
P19	.076	.004	.061	.090
P20	.089	.004	.074	.104

[ns] Not significant at the level of $p < .05$.
All other comparisons were at the significance level of $p < .01$.

these scenarios. Some scenarios were selected and analyzed to explore the relationships between discomfort feelings and vehicle-transportation-agents interactions.

Table VII shows the post hoc test results of the comparison between DLR values in *Following* and *Open Driving* maneuvers. Eighteen out of 20 participants reported to have experienced significantly higher discomfort levels in *Following* than in *Open Driving*. The only difference between *Open Driving* and *Following* maneuvers is that the vehicle is closely behind another vehicle in the *Following* maneuver. The existence of surrounding traffic played as the amplifier of discomfort in these scenarios.

In *Following* maneuvers, vehicle-vehicle interactions occurred as the ego vehicle dynamically maintained a certain headway distance to the leading vehicle. Another scenario involving vehicle-vehicle interactions is merging onto the highway. Maneuver 1 (M1) displayed in Fig. 5(a) is from journey Highway Aggressive 3, and Maneuver 2 (M2) displayed in Fig. 5(b) is from journey Highway Gentle 3.

In M1, the ego vehicle tried to merge into the mainstream on the highway while the yellow car on the right was trying to cut in front of the ego vehicle. The ego vehicle was forced to make a dodge to avoid collision and accelerated to join the mainstream in front of the yellow car. A significant rise in the DLR value can be found between the 155^{th} second and the 158^{th} second of the journey corresponding to M1. In M2, a similar scenario occurred when the ego vehicle yielded to a white car from the mainstream while joining the highway. Although the ego vehicle yielded to the mainstream in the end and avoided the collision, we can still see a considerable rise in the DLR value between the 199^{th} second and the 201^{st} second of the journey corresponding to M2.

Overall, M1 and M2 have revealed a crucial factor in human discomfort: the right-of-way. The conflict in the right-of-way between the ego vehicle and other vehicles might significantly harm human discomfort in AVs. Besides M1 and M2, some other scenarios also demonstrated the negative influence on human discomfort of having an unclear definition or execution of right-of-way. Maneuver 3 (M3) in Fig. 5(c) was from journey Rural Aggressive 3, displayed along with the DLR record. Maneuver 4 (M4) in Fig. 5(d) was from Rural Gentle 3, displayed along with the DLR record.

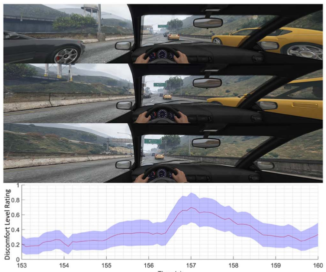
In M3, the ego vehicle and the vehicle in the opposite lane entered the intersection at a similar time. The ego vehicle was going straight, and the other vehicle was to take a left turn. However, the ego vehicle decelerated to a complete stop to yield to the other vehicle. A sharp discomfort can be identified between the 115^{th} second and the 118^{th} second of the journey corresponding to M3. A similar occasion happened with M4. The ego vehicle was following another vehicle in front while the leading vehicle suddenly braked and unexpectedly yielded a left-turning vehicle. A similar sudden rise of discomfort can be found between the 146^{th} second and the 149^{st} second of the journey corresponding to M4. These are some examples of right-of-way conflicts in vehicle-vehicle interactions.

In addition to vehicle-vehicle interactions, right-of-way conflicts also exist within vehicle-pedestrian interactions. In unprotected turnings, there exist chances where the vehicle has to yield to crossing pedestrians. Although the right-of-way is very clear in such scenarios, passengers might still feel uncomfortable when such interaction occurs. Two maneuvers involving vehicle-pedestrian interactions at unprotected turns were selected here for analysis. Maneuver 5 (M5) in Fig. 5(e) was from journey City Gentle 2, and Maneuver 6 (M6) in Fig. 5(f) was from City Normal 1.

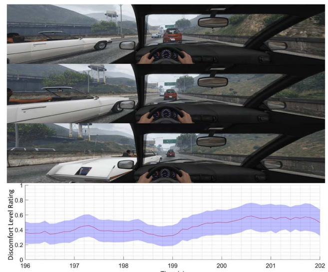
In M5, the ego vehicle took an unprotected right turn with the existence of a crossing pedestrian. The ego vehicle successfully braked and yielded to the pedestrian. However, there was still a significant increase in DLR between the 45^{th} second and the 47^{st} second of the journey corresponding to M5. In M6, the ego vehicle was taking an unprotected left turn while coming across a pedestrian crossing the street. Similarly, the vehicle successfully stopped and yielded to the pedestrian, while participants still perceived a significant discomfort between the 74^{th} second and the 76^{st} second of the journey corresponding to M6. The vehicle executed the right-of-way correctly on these two occasions, while participants still reported significant discomfort. One possible reason could be that the vehicle failed to take more proactive action against the crossing pedestrian, and participants might perceive risks of a collision with the pedestrian due to the late response of the vehicle.

F. Driving Slow on Highway

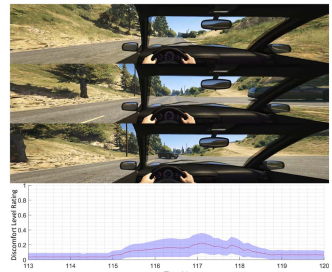
Another interesting finding of the analysis is that participants could feel uncomfortable if the vehicle was driving at a low velocity on the highway. We have found discomfort feelings related



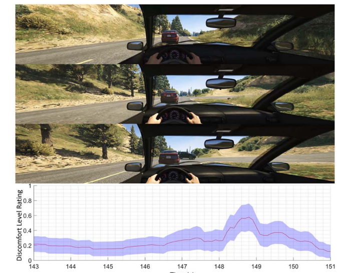
(a) Maneuver 1: Dodging and overtaking another vehicle while merging.



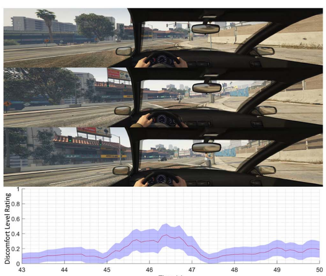
(b) Maneuver 2: Yielding to another vehicle while merging.



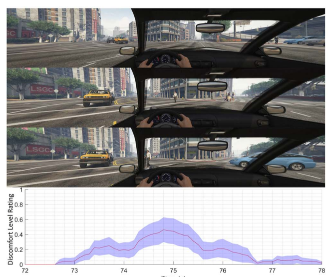
(c) Maneuver 3: Yielding to a left-turn vehicle while driving straight.



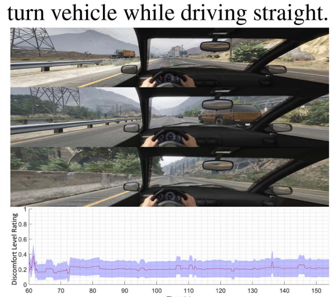
(d) Maneuver 4: Braking when the leading vehicle yielded to a left-turn vehicle.



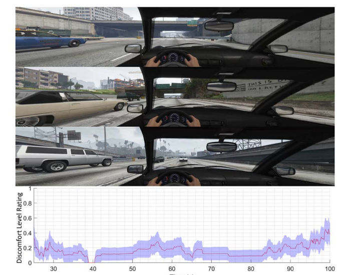
(e) Maneuver 5: Yielding to a pedestrian while turning right.



(f) Maneuver 6: Yielding to a pedestrian while turning left.



(g) Maneuver 7: Cruising at 55mph on the left lane of the highway.



(h) Maneuver 8: Cruising at 55mph on the right lane of the highway.

Fig. 5. Selected scenarios that demonstrated the effects of some special maneuvers on discomfort levels. Each sub-figure displays the scenario and corresponding DLR values during the scenario. The red line in the DLR charts represents the mean discomfort level rating across all 20 participants. The 90% confidence interval of each mean value was also calculated and plotted as the light blue area around the means. The confidence interval provides a visualized estimate of the statistical significance of discomfort changes. If the confidence intervals of two means do not overlap, it means that zero is not within the 90% confidence interval of the difference between the two values [35]. Maneuver 1 was taken from journey Highway Aggressive 3. The vehicle was performing *Merging* maneuver when it dodged and overtook a vehicle cutting lane. Maneuver 2 was taken from journey Highway Gentle 3. The vehicle was performing *Merging* maneuver when it yielded to a vehicle from the mainstream. Maneuver 3 was taken from journey Rural Aggressive 3. The vehicle was performing *Deceleration* maneuver when it yielded to a left-turn vehicle. Maneuver 4 was taken from journey Rural Gentle 3. The vehicle was performing *Deceleration* maneuver when it reacted to the sudden brake of the leading vehicle yielding to a left-turn vehicle. Maneuver 5 was taken from journey City Gentle 2. The vehicle was performing *Turn Right* maneuver when it yielded to a pedestrian. Maneuver 6 was taken from journey City Normal 1. The vehicle was performing *Turn Left* maneuver when it yielded to a pedestrian. Maneuver 7 was taken from journey Highway Gentle 2. The vehicle was performing *Open Driving* maneuver on the left lane of the highway at 55 mph. Maneuver 8 was taken from journey Highway Gentle 3. The vehicle was performing *Open Driving* maneuver on the right lane of the highway at 55 mph.

to driving slowly on two highway journeys. Maneuver 7 (M7) in Fig. 5(g) occurred with journey Highway Gentle 2, and Maneuver 8 (M8) in Fig. 5(h) occurred with journey Highway Gentle 3.

In M7 and M8, the vehicle executed an *Open Driving* maneuver. The vehicle was driving at 55mph on the left and the right lanes of the highway in M7 and M8, respectively. Fig. 5(g) and (h) show that participants reported mild but persistent discomfort all along these two maneuvers. In *Open Driving* maneuvers under other driving styles or road types, no such form of persistent discomfort feeling was found.

G. Mixed Logit Model on Discomfort Levels

With a basic understanding of the factors that influence passenger discomfort in AVs, a mixed logit model was fitted with the main effects of vehicular maneuver, driving style, and road type as the predictors. A new categorical variable with two levels, *no discomfort* and *discomfort*, was generated as the outcome of the model. The discomfort level variable was generated based on the distribution of DLR values in the dataset. The distribution of DLR values in the dataset is plotted in Fig. 6. The frequency of samples falling into each DLR value range is represented on a logarithmic scale. Overall, DLR values were distributed with an imbalance towards zero and with a gap between zero and. 24. Therefore, samples with DLR value of zero were classified as *no discomfort* samples, and the others were classified as *discomfort* samples.

The mixed logit modeling results are displayed in Table VIII. With the b coefficients, the influence of the factors on participants' discomfort levels can be interpreted. A positive coefficient indicates that the condition increases the probability of feeling uncomfortable compared to the reference level, which is shown in the parentheses beside the variable name. The absolute value of the coefficient shows the effect size of the influence.

For vehicular maneuver, *Acceleration* was selected as the reference level. Among other maneuvers, all were found to be significant ($p < .01$). *Following* ($b = 1.210$, $SE = .014$), *Lane Switch Right* ($b = .828$, $SE = .020$), and *Turn Right* ($b = .715$, $SE = .022$) were the three maneuvers that would the most likely to cause *discomfort*. Whereas *Open Driving* ($b = -.101$, $SE = .014$) was the only maneuver that would less likely to cause *discomfort* compared to *Acceleration* maneuver.

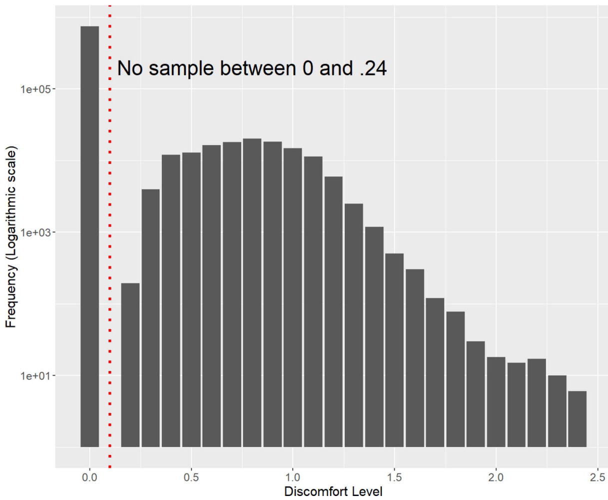


Fig. 6. The distribution of DLR values in the data.

TABLE VIII
MODEL COEFFICIENTS OF THE MIXED LOGIT MODEL

	b	Standard Error	z
Fixed Effects			
(Intercept)	-2.067	.106	-19.4
Vehicular maneuver (*Acceleration*)			
• *Deceleration*	.264	.018	-19.4
• *Open Driving*	-.101	.014	-7.4
• *Following*	1.210	.014	86.5
• *Lane Switch Left*	.414	.020	21.2
• *Lane Switch Right*	.828	.020	41.8
• *Turn Left*	.360	.022	16.7
• *Turn Right*	.715	.022	32.1
Driving style (*Aggressive*)			
• *Gentle*	-.014^{ns}	.007	-1.9
• *Normal*	-1.025	.009	-113.8
Road type (*City*)			
• *Highway*	.009^{ns}	.009	1.0
• *Rural*	-.219	.009	-23.4
Random Effects			
(Intercept)	1.195		
Fit Metrics			
Log Likelihood	-316150.6		
Akaike Information Criterion	632327.2		
McFadden's Pseudo R^2	.084		

^{ns} Not significant at the level of $p < .05$.
All other comparisons were at the significance level of $p < .01$.
The reference level of each variable is displayed along the variable name.

Aggressive was selected as the reference level for driving style. *Gentle* ($b = -.014$, $SE = .007$) did not show a significant ($p < .05$) difference than *Aggressive* in causing *discomfort*. *Normal* ($b = -1.025$, $SE = .009$) would significantly decrease the probability of causing *discomfort*.

City was selected as the reference level for road type. No significant difference was found for the probability of *discomfort* occurring in *Highway* journeys ($b = .009$, $SE = .009$). While there was a lower chance of participants getting into *discomfort* in *Rural* journeys ($b = -.219$, $SE = .009$).

The model further confirmed and expanded the previous analyses on the main effects of vehicular maneuver and driving style. *Following*, *Lane Switch Right*, and *Turn Right* were the three maneuvers that the most likely to cause *discomfort*, which confirmed the untested observations in the descriptive analyses. The model coefficients also suggested that *Normal* style was the most comfortable style in this study. For road type, the model suggested that participants were more likely to feel uncomfortable in *City* and *Highway* roads than in *Rural* roads. The reason might be that the discomfort-related maneuvers, e.g., *Following*, *Lane Switch Right*, occurred less frequently in *Rural* roads than in the other two road types.

IV. DISCUSSION

This study explored influential factors of passenger discomfort in AVs. Based on a simulator-based experimental covering 20 participants, more than 25 hours of subjective discomfort ratings of AV journeys were gathered and analyzed. Descriptive analyses and MANOVA were performed to explore the influences from various factors on discomfort. With the results reported in the previous section, implications and potential AV design insights are further discussed.

A. Situational Awareness and Discomfort

In Section III-C, a notable dissimilarity emerged in discomfort levels between left- and right-heading lateral maneuvers. Participants reported notably higher discomfort during right-heading lateral maneuvers. This variance in perceived discomfort levels could be attributed to differing situational awareness (SA) levels. Notably, participants were positioned on the left-hand side of the vehicle during the stimuli, resulting in a broader field-of-view (FOV) over traffic to their left compared to their right, as illustrated in Fig. 3. A better FOV over the left might have enhanced participants' SA of the traffic on the vehicle's left side, allowing participants to gain extra confidence and less discomfort in left-heading maneuvers. In contrast, the limited SA of the right side might have increased the uncertainty over whether the condition allowed a right-heading maneuver. The difference in SA might influence the confidence in completing a maneuver. Consequently, less discomfort was perceived in left-heading maneuvers than in right-heading maneuvers.

Morales et al. [19] underscored the significance of visibility in shaping human discomfort within autonomous vehicles (AVs). Their study uncovered a correlation between diminished visibility and heightened discomfort among passengers. To address this concern, they proposed a visibility model for indoor navigation, with potential integration into motion planning algorithms. Moreover, optimizing HMI designs to enhance passengers' perception of surrounding traffic represents another approach to improving comfort within AVs. Chang et al. [36] further investigated this by examining the impact of SA levels displayed on in-vehicle screens on passenger trust and comfort. By varying the information presented through the HMI regarding surrounding traffic, they found that an optimal balance can be achieved to enhance both trust and comfort levels.

In summary, right-heading maneuvers were found to be significantly more uncomfortable than left-heading maneuvers in this study. The disparity in SA conditions may be responsible for the difference. Incorporating SA considerations in motion planning algorithms and optimizing HMI designs for improved SA are potential strategies to enhance passenger comfort in AVs.

B. Lateral Control of Autonomous Vehicles

In the study, lateral maneuvers, such as lane switches and turns, were observed to elicit significantly higher levels of discomfort compared to longitudinal maneuvers. Despite their shorter duration (N = 5,289) relative to longitudinal maneuvers (N = 38,696) over the course of the experiment, lateral maneuvers significantly contributed to the overall discomfort experienced during trips. Consequently, there is a need for increased emphasis and further investigation into the factors influencing discomfort during such lateral maneuvers.

Various studies have examined the influence of lateral kinematics, i.e., trajectory, acceleration, and jerk, on passenger discomfort in AVs. The study by Peng et al. [37] found that lateral kinematics had a higher impact on discomfort levels compared to longitudinal kinematics, which agreed with the findings in this study. The widely accepted consensus suggests a positive correlation between higher lateral acceleration and increased passenger discomfort [22], [38], [39]. These results underscore the importance of minimizing lateral accelerations during lateral maneuvers. Conversely, Hellem et al. [15] found that a stronger lateral jerk at the beginning of lane-switching maneuvers contributed positively to overall comfort levels. This may be attributed to passengers' perception of proactive maneuvering capability. Additionally, the naturalness of the vehicle trajectory [12] emerges as another significant factor affecting human comfort within AVs.

In addition to lateral kinematic factors, SA levels could have contributed to heightened discomfort during lateral maneuvers. In this study, participants were positioned facing forward, giving them a more comprehensive view of traffic ahead than the vehicle's sides. Consequently, during lateral maneuvers, participants faced decreased SA in the direction of the maneuver. To address this issue, similar to discussions regarding left- and right-heading maneuvers, the integration of SA-aware motion planning algorithms and the implementation of SA-enhancing HMI designs are the potential solutions.

In summary, findings in this study indicate that lateral maneuvers significantly contribute to passenger discomfort during autonomous vehicle (AV) journeys. Factors such as lateral kinematics play crucial roles in shaping passenger comfort within AVs. Additionally, decreased SA levels on the vehicle's sides likely elicit discomfort during lateral maneuvers. Overall, the complexity of discomfort factors in lateral maneuvers necessitates further investigation and understanding.

C. Interaction With Other Road Users

The impact of the presence of other road users on passenger discomfort in AVs was initially investigated by comparing *Open Driving* and *Following* maneuvers. Significantly elevated discomfort levels were observed during *Following* maneuvers compared to *Open Driving*. These results underscore the critical role of nearby traffic in passenger discomfort within AVs. Dillen et al. [40] conducted a field study revealing that the presence or proximity of a lead vehicle led to heightened Galvanic Skin Response, increased heart rate, and elevated eye movement entropy levels among AV passengers. These physiological signal responses were interpreted as indicators of heightened discomfort experienced by participants. The researchers attributed the discomfort to increased safety apprehensions associated with the presence or proximity of the lead vehicle, thus exacerbating passenger discomfort. These findings suggest that the presence of surrounding traffic raises safety concerns, consequently impacting passenger comfort.

The presence of other road users introduces another significant factor: the right-of-way. Various scenarios were investigated to identify instances where conflicts over right-of-way occurred, resulting in observed discomfort. These scenarios covered right-of-way conflicts during highway merging, unsignalized intersections, and encounters between vehicles and pedestrians. In scenarios without human road users, such as fully AV traffic, the connected AV (CAV) technology [41] offers a solution to right-of-way conflicts. However, the mixed traffic scenario poses greater challenges, with human drivers, micro-mobility road users, and pedestrians sharing the road with AVs. The unpredictability and diversity in human behaviors heighten the difficulty in determining right-of-way. Moreover, the lack of effective communication between human road users and AVs increases the challenge of coordinating their behaviors. Addressing these challenges requires the development of a comprehensive and well-defined taxonomy outlining right-of-way principles in mixed traffic scenarios [42], [43]. Additionally, the establishment of efficient communication channels between AVs and human road users is essential to coordinate their actions in accordance with established right-of-way paradigms [44].

In this study, participants reported discomfort during interactions between the AV and other road users. This disparity in discomfort levels may come from risen safety concerns due to the presence of surrounding traffic, consequently amplifying perceived discomfort. Furthermore, the coexistence of various road users inevitably leads to right-of-way conflicts, potentially resulting in uncomfortable situations for AV passengers. CAV technology presents a promising solution to mitigate right-of-way conflicts in fully AV traffic scenarios. However, in mixed traffic environments involving human road users, addressing right-of-way challenges requires the development of a well-defined taxonomy outlining right-of-way principles in diverse scenarios, along with the establishment of effective communication channels between AVs and other human road users.

D. Leveraging Safety and Passenger's Preferences in Autonomous Vehicle Designs

In Section III-F, our analysis revealed two instances of discomfort reported by participants during *Open Driving* maneuvers. Through careful consideration of various factors and feedback from select participants, it became evident that the underlying cause of this discomfort was attributed to the vehicle's slow speed while cruising on the highway.

Operating at or slightly above the speed limit is a common behavior among human drivers [45]. In the maneuvers analyzed in Section III-F, despite the vehicle adhering to legal speed limits, passengers experienced discomfort. This discomfort may have come from the vehicle's velocity not aligning with passengers' accustomed preferences. Aligning the AV's velocity with passengers' preferred velocity profiles could enhance the perceived naturalness and comfort [37], [46]. Understanding typical driving behaviors and adjusting the AV's control strategy accordingly could contribute to making AVs more comfortable for passengers.

Despite the potential advantages of tailoring AV control strategies to enhance passenger comfort, such adaptations must adhere to certain safety restrictions. As discussed in previous sections, factors contributing to passenger discomfort in AVs are closely linked to safety concerns. This underscores the relationship between safety and comfort, emphasizing the need to establish boundaries regarding the extent to which AVs can accommodate passenger preferences. Additionally, considering the differing capabilities of human drivers and automated controllers, these boundaries may not solely align with existing traffic laws and regulations, which are established based on human driver traffic. It may be necessary to recalibrate safety boundaries based on the capabilities of AVs and the traffic context, whether it involves exclusively AV traffic or mixed traffic scenarios. Moreover, adaptation can also occur from the passenger's perspective. In the concept of bilateral adaptation between AV and passenger, the AV has a responsibility to educate passengers and dissuade them from endorsing behaviors that may compromise safety or vehicle performance [47]. In summary, enhancing passenger comfort in AVs requires leveraging safety considerations with passenger preferences, which is a collaborative effort that involves policymakers, AV designers, and AV users.

E. Future Works

In this study, a relatively concentrated and inclined demographic group was employed. The participants were concentrated between 22 and 38 years of age, and 15 of them were male, with another five female participants. The inclination reflected the demographic groups with more positive attitudes towards AVs in the future. In [48] and [49], the researchers found that users between the ages of 18 and 44 held more positive attitudes toward AVs than older users, with users between the ages of 25 and 34 having the most positive attitudes. Similarly, male users were also found to have more positive attitudes toward AVs than female users. Based on these findings, we anticipated that users from these age and gender groups were also more likely to be the first adopters of AVs in the future. Focusing on these demographic groups can potentially yield icebreaking achievements by improving the user experience for the early-bird users of AVs.

However, the concentrated demographic backgrounds in this study may negatively influence the generalization of the conclusions from this study. Therefore, in future studies, broader coverage of different age groups and a more balanced gender distribution can be considered.

V. Conclusion

In summary, this paper employed a human-in-the-loop experimental approach utilizing a high-fidelity autonomous driving simulator with 6-DOF motion to investigate factors contributing to human discomfort in AVs. Through a series of autonomous driving journeys, a comprehensive exploration of these discomfort factors was conducted. The experimental data were thoroughly analyzed to assess the effects of various factors on human discomfort levels in AVs, with quantitative analysis employed to measure the impacts of key factors. The study identified and investigated numerous factors influencing human discomfort in AVs, leading to an extensive discussion on potential solutions aimed at alleviating passenger discomfort. The findings of this study, along with the relevant solutions, are summarized as follows:

- SA of surrounding traffic influences discomfort in AVs: SA-aware motion planning algorithms and SA-enhancing HMI designs are necessary to alleviate passenger discomfort induced by insufficient SA.
- Lateral maneuvers are more likely to induce discomfort than longitudinal maneuvers, warranting further investigation into strategies for lateral maneuvering.
- Interaction with other road users is likely to cause discomfort: CAV technology presents a viable solution to right-of-way conflicts in fully AV traffic. Establishing a well-defined taxonomy of right-of-way and implementing effective communication channels between AVs and other road users are imperative for addressing right-of-way conflicts in mixed traffic scenarios involving human road users.
- Ignoring passenger preferences for vehicle control leads to discomfort: AVs can be engineered to adapt to passenger preferences within certain safety restrictions. These safety restrictions should be adjusted according to the capabilities of AVs. Additionally, AVs can influence passenger preferences to adhere to certain rules. These joint efforts can make the AV more comfortable for the passenger.

References

[1] T. Litman, "Autonomous vehicle implementation predictions: Implications for transport planning," *Victoria Transp. Policy Inst.*, 2023. [Online]. Available: https://www.vtpi.org/avip.pdf

[2] P. Fernandes and U. Nunes, "Platooning with IVC-enabled autonomous vehicles: Strategies to mitigate communication delays, improve safety and traffic flow," *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 1, pp. 91–106, Mar. 2012.

[3] C. Rödel, S. Stadler, A. Meschtscherjakov, and M. Tscheligi, "Towards autonomous cars: The effect of autonomy levels on acceptance and user experience," in *Proc. 6th Int. Conf. Automot. User Interfaces Interactive Veh. Appl.*, 2014, pp. 1–8, doi: 10.1145/2667317.2667330.

[4] J. D. Power, "Mobility pipe dreams? J. D. Power and SurveyMonkey uncover shaky consumer confidence about the future," 2019. Accessed: Oct. 23, 2019. [Online]. Available: https://www.jdpower.com/business/press-releases/2019-mobility-confidence-index-study-fueled-surveymonkey-audience/

[5] B. Schoettle and M. Sivak, "A survey of public opinion about connected vehicles in the us, the UK, and Australia," in *Proc. IEEE Int. Conf. Connected Veh. Expo*, 2014, pp. 687–692.

[6] N. Kalra and S. M. Paddock, "Driving to safety: How many miles of driving would it take to demonstrate autonomous vehicle reliability?," *Transp. Res. Part A, Policy Pract.*, vol. 94, pp. 182–193, 2016.

[7] P. Koopman and M. Wagner, "Autonomous vehicle safety: An interdisciplinary challenge," *IEEE Intell. Transp. Syst. Mag.*, vol. 9, no. 1, pp. 90–96, Spring 2017.

[8] E. Frazzoli, M. A. Dahleh, and E. Feron, "Real-time motion planning for agile autonomous vehicles," *J. Guid., Control, Dyn.*, vol. 25, no. 1, pp. 116–129, 2002.

[9] M. J. Griffin, "Discomfort from feeling vehicle vibration," *Veh. Syst. Dyn.*, vol. 45, no. 7/8, pp. 679–698, 2007.

[10] M. J. M. Nor, M. H. Fouladi, H. Nahvi, and A. K. Ariffin, "Index for vehicle acoustical comfort inside a passenger car," *Appl. Acoust.*, vol. 69, no. 4, pp. 343–353, 2008.

[11] A. Mezrhab and M. Bouzidi, "Computation of thermal comfort inside a passenger car compartment," *Appl. Thermal Eng.*, vol. 26, no. 14/15, pp. 1697–1704, 2006.

[12] M. Elbanhawi, M. Simic, and R. Jazar, "In the passenger seat: Investigating ride comfort measures in autonomous cars," *IEEE Intell. Transp. Syst. Mag.*, vol. 7, no. 3, pp. 4–17, Fall 2015.

[13] V. Domova, R. Currano, and D. Sirkin, "Toward a high-level integrative comfort model in autonomous driving," in *Proc. Adjunct 14th Int. Conf. Automot. User Interfaces Interactive Veh. Appl.*, 2022, pp. 141–144.

[14] C. Strauch et al., "Real autonomous driving from a passenger's perspective: Two experimental investigations using gaze behaviour and trust ratings in field and simulator," *Transp. Res. Part F, Traffic Psychol. Behav.*, vol. 66, pp. 15–28, 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1369847818307265

[15] H. Bellem, B. Thiel, M. Schrauf, and J. F. Krems, "Comfort in automated driving: An analysis of preferences for different automated driving styles and their dependence on personality traits," *Transp. Res. Part F, Traffic Psychol. Behav.*, vol. 55, pp. 90–100, 2018. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1369847817301535

[16] F. Hartwich, M. Beggiato, and J. F. Krems, "Driving comfort, enjoyment and acceptance of automated driving—Effects of drivers' age and driving style familiarity," *Ergonomics*, vol. 61, no. 8, pp. 1017–1032, 2018, doi: 10.1080/00140139.2018.1441448.

[17] S. Yan, C. Liu, and J. Cao, "Comfort-based trajectory and velocity planning for automated vehicles considering road conditions," *Int. J. Automot. Technol.*, vol. 22, no. 4, pp. 883–893, 2021.

[18] D. Oborne, "Vibration and passenger comfort," *Appl. Ergonom.*, vol. 8, no. 2, pp. 97–101, 1977.

[19] Y. Morales et al., "Visibility analysis for autonomous vehicle comfortable navigation," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2014, pp. 2197–2202.

[20] M. P. De Looze, L. F. Kuijt-Evers, and J. Van Dieen, "Sitting comfort and discomfort and the relationships with objective measures," *Ergonomics*, vol. 46, no. 10, pp. 985–997, 2003.

[21] L. Zhang, M. G. Helander, and C. G. Drury, "Identifying factors of comfort and discomfort in sitting," *Hum. Factors*, vol. 38, no. 3, pp. 377–389, 1996, doi: 10.1518/001872096778701962.

[22] H. Bellem, T. Schönenberg, J. F. Krems, and M. Schrauf, "Objective metrics of comfort: Developing a driving style for highly automated vehicles," *Transp. Res. Part F, Traffic Psychol. Behav.*, vol. 41, pp. 45–54, 2016. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S136984781630064X

[23] H. Su and Y. Jia, "Estimating human comfort levels in autonomous vehicles based on vehicular behaviors and physiological signals," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2023, pp. 9865–9870.

[24] O. Carsten and M. H. Martens, "How can humans understand their automated cars? HMI principles, problems and solutions," *Cognition, Technol. Work*, vol. 21, no. 1, pp. 3–20, 2019.

[25] H. Su and Y. Jia, "Computational modeling of human comfort in automated vehicles from maneuvering behaviors," in *Proc. IEEE 25th Int. Conf. Intell. Transp. Syst.*, 2022, pp. 723–729.

[26] M. G. Helander and L. Zhang, "Field studies of comfort and discomfort in sitting," *Ergonomics*, vol. 40, no. 9, pp. 895–915, 1997.

[27] H. Su and Y. Jia, "Study of human comfort in autonomous vehicles using wearable sensors," *IEEE Trans. Intell. Transp. Syst.*, vol. 23, no. 8, pp. 11490–11504, Aug. 2022.

[28] H. Bellem, M. Klüver, M. Schrauf, H.-P. Schöner, H. Hecht, and J. F. Krems, "Can we study autonomous driving comfort in moving-base driving simulators? A validation study," *Hum. Factors*, vol. 59, no. 3, pp. 442–456, 2017.

[29] SAE International, "Taxonomy and definitions for terms related to on-road motor vehicle automated driving systems," *SAE Standard J*, vol. 3016, pp. 1–16, 2014.

[30] G. Kyung and M. A. Nussbaum, "Specifying comfortable driving postures for ergonomic design and evaluation of the driver workspace using digital human models," *Ergonomics*, vol. 52, no. 8, pp. 939–953, 2009.

[31] H. Su, J. Brooks, and Y. Jia, "Development and evaluation of comfort assessment approaches for passengers in autonomous vehicles," *SAE Int. J. Adv. Curr. Practices Mobility*, vol. 5, pp. 2068–2077, 2023.

[32] G. G. Berntson, J. T. Cacioppo, and L. G. Tassinary, *Handbook of Psychophysiology*. Cambridge, U.K.: Cambridge Univ. Press, 2017.

[33] P. J. Gianaros, E. R. Muth, J. T. Mordkoff, M. E. Levine, and R. M. Stern, "A questionnaire for the assessment of the multiple dimensions of motion sickness," *Aviation, Space, Environ. Med.*, vol. 72, no. 2, pp. 115–119, 2001.

[34] R. G. O'Brien and M. K. Kaiser, "MANOVA method for analyzing repeated measures designs: An extensive primer," *Psychol. Bull.*, vol. 97, no. 2, 1985, Art. no. 316.

[35] T. Wright, M. Klein, and J. Wieczorek, "A primer on visualizations for comparing populations, including the issue of overlapping confidence intervals," *Amer. Statistician*, vol. 73, no. 2, pp. 165–178, 2019.

[36] C.-C. Chang et al., "Using a situational awareness display to improve rider trust and comfort with an AV taxi," in *Proc. Hum. Factors Ergonom. Soc. Annu. Meeting*, 2019, pp. 2083–2087.

[37] C. Peng, C. Wei, A. Solernou, M. Hagenzieker, and N. Merat, "User comfort and naturalness of automated driving: The effect of vehicle kinematics and proxemics on subjective response," OSF Preprints osf.io/8hkb5, 2023.

[38] I. Bae, J. Moon, and J. Seo, "Toward a comfortable driving experience for a self-driving shuttle bus," *Electronics*, vol. 8, no. 9, 2019, Art. no. 943. [Online]. Available: https://www.mdpi.com/2079-9292/8/9/943

[39] N. M. Yusof, J. Karjanto, J. Terken, F. Delbressine, M. Z. Hassan, and M. Rauterberg, "The exploration of autonomous vehicle driving styles: Preferred longitudinal, lateral, and vertical accelerations," in *Proc. 8th Int. Conf. Automot. User Interfaces Interactive Veh. Appl.*, 2016, pp. 245–252, doi: 10.1145/3003715.3005455.

[40] N. Dillen, M. Ilievski, E. Law, L. E. Nacke, K. Czarnecki, and O. Schneider, "Keep calm and ride along: Passenger comfort and anxiety as physiological responses to autonomous driving styles," in *Proc. CHI Conf. Hum. Factors Comput. Syst.*, 2020, pp. 1–13, doi: 10.1145/3313831.3376247.

[41] B. Lehmann, H.-J. Günther, and L. Wolf, "A generic approach towards maneuver coordination for automated vehicles," in *Proc. IEEE 21st Int. Conf. Intell. Transp. Syst.*, 2018, pp. 3333–3339.

[42] P. N. Wong, "Who has the right of way, automated vehicles or drivers? Multiple perspectives in safety, negotiation and trust," in *Proc. 11th Int. Conf. Automot. User Interfaces Interactive Veh. Appl.*, 2019, pp. 198–210.

[43] T. Fuest, L. Sorokin, H. Bellem, and K. Bengler, "Taxonomy of traffic situations for the interaction between automated vehicles and human road users," in *Advances in Human Aspects of Transportation*, N. A. Stanton, Ed. Cham, Switzerland: Springer, 2018, pp. 708–719.

[44] Y. E. Song, C. Lehsing, T. Fuest, and K. Bengler, "External HMIs and their effect on the interaction between pedestrians and automated vehicles," in *Intelligent Human Systems Integration*, W. Karwowski and T. Ahram, Eds. Cham, Switzerland: Springer, 2018, pp. 13–18.

[45] P. Schroeder et al., "2011 national survey of speeding attitudes and behaviors [supporting datasets]," Department of Transportation, National Highway Traffic Safety, Tech. Rep. DOT HS 811 865, 2013.

[46] A. V. Kamaraj, J. Lee, J. E. Domeyer, S.-Y. Liu, and J. D. Lee, "Comparing subjective similarity of automated driving styles to objective distance-based similarity," *Hum. Factors*, vol. 66, no. 5, pp. 1545–1563, 2024, doi: 10.1177/00187208221142126.

[47] L. Guo and Y. Jia, "Bilateral adaptation of longitudinal control of automated vehicles and human drivers," *IEEE Trans. Intell. Transp. Syst.*, vol. 24, no. 5, pp. 5663–5671, May 2023.

[48] T. Liljamo, H. Liimatainen, and M. Pöllänen, "Attitudes and concerns on automated vehicles," *Transp. Res. Part F, Traffic Psychol. Behav.*, vol. 59, pp. 24–44, 2018. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1369847818303292
[49] H. Abraham et al., "Autonomous vehicles and alternatives to driving: Trust, preferences, and effects of age," in *Proc. Transp. Res. Board 96th Annu. Meeting*, 2017, pp. 8–12.

Haotian Su (Graduate Student Member, IEEE) received the bachelor's degree from Tsinghua University, Beijing, China, in 2018. He is currently working toward the Ph.D. degree in automotive engineering with the Clemson University International Center for Automotive Research, Greenville, SC, USA. His research interests include human-computer interaction, cognitive engineering, and affective computing.

Yunyi Jia (Senior Member, IEEE) received the B.S. degree from the National University of Defense Technology, Changsha, China, the M.S. degree from the South China University of Technology, Guangzhou, China, and the Ph.D. degree from Michigan State University, East Lansing, MI, USA. He is currently the McQueen Quattlebaum Assistant Professor and the Director of the Collaborative Robotics and Automation (CRA) Lab, Department of Automotive Engineering, Clemson University International Center for Automotive Research (CU-ICAR), Greenville, SC, USA. His research interests include robotics, autonomous vehicles, and advanced sensing systems.