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Toward Personalized Merging Behaviors: Enhancing Automated Vehicle Trust by Adapting to the Driving Style of Surrounding Vehicles

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Abstract— **For successful real-world implementation of automated vehicles, earning trust from other road users is crucial especially in scenarios that require interaction and cooperation such as merging under congestion. While previous research has developed a communication model to improve explicit and implicit intent communication for merging vehicles, this study focuses on the execution phase of the merging maneuver, where the merging vehicle interprets the host vehicle's intent and must decide whether and if so when to merge. As different drivers perceive risk differently, we discovered that risk-averse drivers, classified by their characteristics of following preceding vehicles, prefer merging over longer distances, whereas risk-tolerant drivers expect to merge over shorter distances, as demonstrated through participant experiments. The correlation between the driving style of the host vehicle and the expectations toward merging vehicles indicates that trust toward the merging vehicle can be maximized by tailoring the merging vehicle's decision-making threshold according to the host vehicle's driving style. This study enhances our understanding of the differences in human drivers' expectations and trust within interactive driving scenarios, offering new insights for improving cooperative behavior in automated driving systems.**

I. INTRODUCTION

Automated driving technology is becoming a tangible solution not only for enhancing safety and comfort but also for addressing societal issues by providing robust mobility where there is a driver shortage and to those unable to drive. Establishing trust between humans and automated systems is essential to enhancing social acceptance. Scenarios that require interaction and cooperation among road users remain particularly challenging. One such example is merging under congestion. If there is insufficient space, the merging vehicle must negotiate with the host vehicle to create the necessary space for merging into the main lane.

Previous studies have developed a communication model that offers a comprehensive view of this interactive driving scenario, elucidating effective explicit and implicit intent communication methods for merging vehicles to enhance the level of trust [1] [2]. Building on this foundation, our study focuses on the subsequent executing phase, where the merging vehicle must first assess the host vehicle's intention to give way before deciding whether to initiate the merging maneuver.

To model decision-making for merging, a mathematical model called Gap Acceptance theory [3] is commonly used. The model captures how drivers evaluate and decide whether there is a sufficiently large gap in oncoming traffic or adjacent lanes for them to safely enter, merge, or cross [4]. Dong *et al.* proposed a learning-based method to estimate merging intentions that can organize historical time-series data [5]. An optimization approach that formulates the problem as a partially observable Markov decision process (POMDP) can deal with the uncertainty of the estimated intent [6]. However, these studies do not take into account the perspective of the host vehicle, which could lead to behavior that is perceived as untrustworthy.

Few studies have evaluated the subjective assessment of decision-making conditions in merging scenarios from an external perspective [7] [8]. Although minimizing perceived risk is a prime criterion to building trust [7], efficiency is also a crucial aspect during merging [8]. As merging vehicles approach the lane endpoint and travel at higher speeds, host vehicles tend to expect merges to occur over shorter gaps. This expectation likely arises from the potential cost disadvantages associated with widening the gap [9].

Prioritizing efficiency results in a shorter distance between the vehicles, which inherently increases risk. However, different drivers perceive risk differently; a distance that one driver finds comfortable may not be perceived the same by another. Therefore, adapting decision-making thresholds according to the estimated risk sensitivity of the host vehicle could help align the host driver's expectations with the actual merging behavior. This alignment, in turn, can enhance the host driver's level of trust [10].

Several studies have personalized the control algorithm of automated vehicles according to the driving style of the on-board driver in interactive driving scenarios [11] - [13]. Moreover, Wang *et al.* studied the effect of the host vehicle's social preference on merging decisions [14]. However, to the best of the authors' knowledge, no prior research has investigated adapting the merging behavior of an automated vehicle to the driving styles of the surrounding vehicles.

Focusing on the driving styles of the host vehicle, this paper initially formulates several hypotheses within a theoretical framework. We then present the experimental design to investigate these hypotheses. Subsequently, we conduct the experiment including subjective evaluation from the host vehicle's perspective, considering various merging decision-making thresholds. Finally, we analyze and discuss the results. Our contributions can be summarized as follows:

- Experimental findings suggest that the way to make space for the merging vehicle varies according to the host vehicle's driving style.

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- We found that risk-averse drivers in the host vehicles anticipate merging over longer distances, whereas risk-tolerant drivers expect merging over shorter distances.
- By tailoring the decision-making threshold of the automated merging vehicle to the perceived host vehicles' driving styles, it is possible to maximize the level of trust toward automated vehicles.

II. THEORETICAL FRAMEWORK

Reacting Behavior: In the negotiation between the merging vehicle and the host vehicle, the host vehicle conveys its acceptance decision through relative longitudinal positioning after observing the merging intent, which is a crucial form of implicit communication [2]. Research has found that reactions to the perceived risk from surrounding vehicles vary according to driving styles [15]. Therefore, the reactions should differ based on the driving style; drivers who are sensitive to risk are expected to respond with greater deceleration than those who are risk-tolerant. In addition, how the host vehicle makes space for the merging vehicle could be a clue to estimating the host vehicle's driving style.

Expectations: After reacting to the merging vehicle, the host vehicle expects the merging vehicle to behave in a certain way based on everyday driving experiences [16]. These expectations toward automated vehicles vary depending on the human driver's own driving style [17]. Drivers with specific driving styles tend to expect similar characteristics in automated vehicles, and the perceived trust is higher when the driving style of the automated vehicle aligns with that of the driver [18]. Therefore, risk-tolerant drivers are anticipated to prefer merging over shorter gaps, whereas risk-averse drivers prefer longer gaps.

Perceived Trust: The more closely an automated vehicle's behavior aligns with the expectations of human drivers, the greater the level of trust it generates [10]. In the merging scenario, the inherent trade-off relationship between safety and efficiency influences trust [7] [8]. Additionally, considering the difference in risk perception among human drivers, this study posits that trust formation is influenced by driving styles even in the same decision-making threshold.

Based on the above observations, we hypothesize as follows: **(H1)** the host vehicle's driving style determines how it makes space for the merging vehicle; the deceleration made by risk-averse drivers is greater than that made by risk-tolerant drivers; **(H2)** different drivers have different expectations; risk-tolerant drivers anticipate an efficient merging (i.e. with a short gap), whereas risk-averse drivers anticipate a safe merging (i.e. with a large gap); and that **(H3)** the smaller the discrepancy between expected and actual behavior, the higher the level of trust that is engendered; risk-tolerant drivers tend to trust an efficient merge, while risk-averse drivers prefer a safe merge.

III. METHODOLOGY

To validate these hypotheses, this study initially determines the driving styles of participants and subsequently gathers their expectations and subjective evaluations from the host vehicle's perspective. We employ a driving simulator to ensure the consistency and repeatability that is so critical to the initial validation of the experimental principles. This controlled environment allows us to precisely replicate driving scenarios and systematically observe participant responses.

Fig. 1. A participant driving the simulator

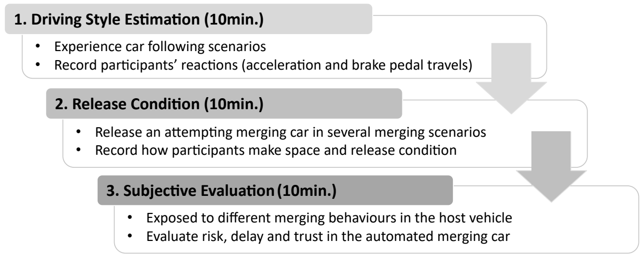

Fig. 2. The three parts or phases of the experimental procedure

A. Driving Simulator

We built a static driving simulator for the merging scenario using CARLA, an open-source simulator for developing automated driving technology that provides photo-realistic visualization capability [19]. Fig. 1 shows an overview of the driving simulation setup, which includes a Logitech G29 steering wheel and pedal controller that accepts driver inputs and three curved screens that cover the peripheral view.

B. Experimental Design

Each experiment took a total of about 30 $\mathrm{minutes}$. Having passed an initial practice session to acclimatize to driving in the simulation environment, the participants experienced the following three parts, as illustrated in Fig. 2:

1) Driving Style Estimation: In this paper, we categorize participants' driving styles based on how they perceive risks to surrounding vehicles. This can be identified by the relative velocity and distance between the lead and the ego vehicle at the brake initiation in a car-following scenario [20]. In the first experimental phase, participants follow a lead vehicle that engages in repeated cycles of acceleration and deceleration, within a range of +1.2 $\mathrm{m/s^2}$ to -2.0 $\mathrm{m/s^2}$ and speeds between 0 $\mathrm{km/h}$ and 40 $\mathrm{km/h}$. The recorded participants' brake pedal travels throughout this process allows us to analyze the precise timing of their responses to varying traffic risk conditions, providing insights into driving styles.

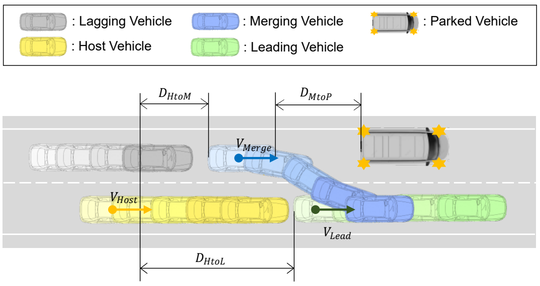

Fig. 3. The dimensions of the experimental setup

In reality, the interplay of various factors, such as psychological influences and driving skills, complicates the isolation of driving styles solely from the risk perception. However, this study classifies driving styles based on observable behavior, as this approach is feasible in the actual traffic flow.

2) Releasing Condition: To understand the reactions and merging expectations of the participants, we investigate how they encourage the merge. With reference to the road geometry shown in Fig. 3, participants drive the host vehicle in the right hand side lane of a simulated dual carriageway urban road at a speed of $V_{Host} = 40$ km/h. Initially, they are instructed to maintain a specific following distance with a time headway of 1.3 seconds to a constantly running preceding car at a speed of $V_{Lead} = 40$ km/h. Then, a parked vehicle appears and blocks the left hand side lane. After observing the merging intent of a vehicle running in that left lane, the participant creates a gap to let the merging vehicle into their lane. By pulling a paddle lever located behind the steering wheel, the participant can prompt the merging vehicle to execute a lane change, as illustrated in Fig. 4. Throughout this scenario, we measure how the participant creates the gap for the merging vehicle and the release conditions. The experimental design follows a 2 x 2 x 2 factorial structure, considering driving styles, the relative speed between the host vehicle and the merging vehicle, and the criticality that is implemented by the distance to the merging endpoint, marked by the back of the parked vehicle.

TABLE I
EXPERIMENTAL PARAMETERS OF RELEASE CONDITION

Parameter	Value
Driving Style	1. Risk-tolerant / 2. Risk-averse
Relative Velocity	1. Zero ($V_{Merge} = 40$ km/h) / 2. Negative ($V_{Merge} = 20$ km/h)
Criticality	1. Critical ($D_{MtoP} = 50$ m) / 2. Non-critical ($D_{MtoP} = 100$ m)

3) Subjective Evaluation: This part investigates the formation of trust in the merging vehicle under various decision-making thresholds. The host vehicle is automatically controlled, allowing participants to focus solely on understanding the surrounding environment and evaluating the merging vehicle from the host vehicle's perspective. The scenario is the same as in the previous section, where a parked vehicle appears in the left hand side lane, prompting an adjacent running vehicle to initiate a lane change into the host vehicle's lane. The experimental design follows a 2 x 3 x 2 factorial structure, considering driving styles, decision thresholds for executing the merge, and the criticality. Participants were asked to answer a questionnaire to evaluate the merging vehicle's behavior after each scenario, consisting of three subjective questions of 1. perceived risk, 2. perceived delay, and 3. trust in the merging vehicle as illustrated in Fig. 5.

Fig. 4. The participant's view at the time of release

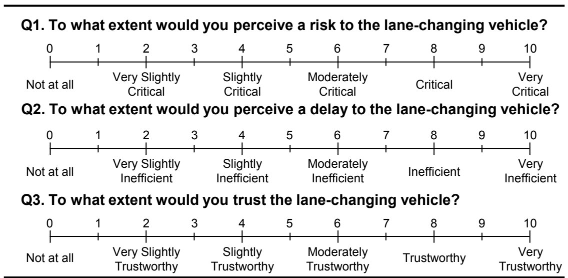

Fig. 5. Questionnaire to evaluate the merging vehicle's behavior

TABLE II
EXPERIMENTAL PARAMETERS OF SUBJECTIVE EVALUATION

Parameter	Value
Driving Style	1. Risk-tolerant / 2. Risk-averse
Decision Threshold THW	1. 0.3 s / 2. 0.6 s / 3. 0.9 s
Criticality	1. Critical ($D_{MtoP} = 50$ m) / 2. Non-critical ($D_{MtoP} = 100$ m)

This experiment was approved by the Faculty of Engineering Research Ethics Committee of the University of Bristol (Ref: 11492). Considering the possibility of motion sickness during the driving simulation experiment, participants were told they were free to stop whenever they wanted.

IV. RESULTS AND DISCUSSION

33 Participants (24 males, 8 females, and 1 other) were recruited within the university community through an online recruitment tool or word of mouth. The age of participants ranged from 23 to 55 years (mean (M) = 36.19, standard deviation (SD) = 9.43). All had valid driving licenses in the UK or EU. The driving experience ranged from 3 to 40 years (M = 14.66, SD = 10.29) and annual mileage ranged from 3200 to 48 000 km (M = 9643.2, SD = 5410.8).

A. Driving Style Classification

During the car-following scenario experiments, the timing of brake pedal application is analyzed by plotting the inverse

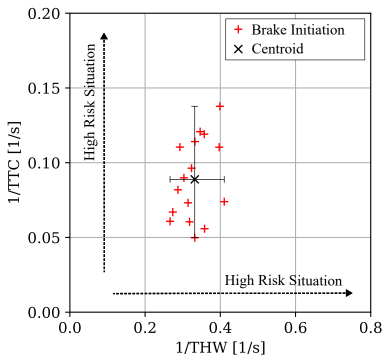

Fig. 6. Plot of every brake initiation and a centroid of an individual participant during the car-following scenario

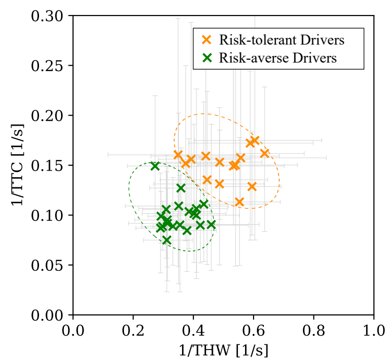

Fig. 7. Aggregation of all the participants and clustering into two categories of driving styles

of the Time-to-Collision (TTC) on the y-axis and the inverse of Time Headway (THW) on the x-axis. Fig. 6 shows brake initiations from all the car-following scenarios as well as the centroid of these data points for each participant. The centroids from all the participants are then plotted and clustered using the k-means algorithm, which partitions n observations into k clusters based on proximity in Euclidean distance as shown in Fig. 7. The clustering process enable us to categorize participants into two distinct groups based on their driving behaviors. The first group comprises drivers who have a propensity of risk-increasing behaviors, which we refer to as 'risk-tolerant drivers.' In contrast, the second group consists of drivers who behave a tendency of risk-decreasing behaviors, which we denote as 'risk-averse drivers.'

B. Reaction and Expectations

In the second experimental phase, where the participant releases the merging vehicle to let it in, we analyze how participants create space after observing the merging vehicle's intent, focusing on deceleration rates and the gap between the merging and the host vehicle. As summarized in Table III, the results of the three-way analysis of variance (ANOVA) indicate significant differences in deceleration rates based on driving style and relative speed. A significance level of $< .05$ was adopted for statistical analysis. Risk-tolerant drivers exhibited lower-intensity deceleration rates (M = -

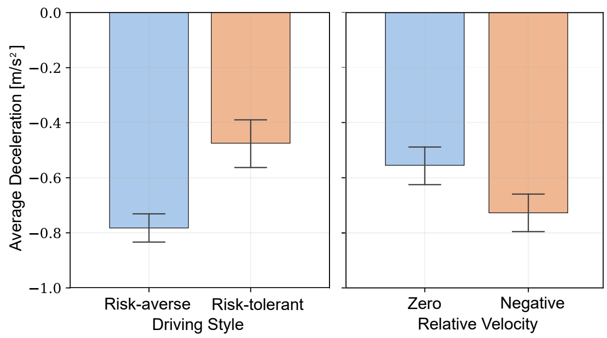

Fig. 8. The average deceleration of the host vehicle when creating the gap to the merging vehicle according to the driving style of the host vehicle (H1) and relative velocity (mean and 95% confidence interval).

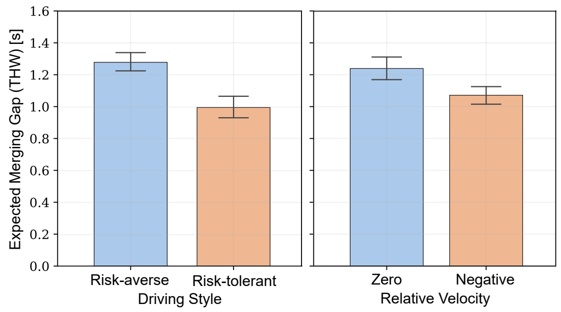

Fig. 9. The expected time gap between the merging and the host vehicle at the time of release according to the driving style of the host vehicle (H2) and relative velocity (mean and 95% confidence interval)

0.47 $\mathrm{m/s^2}$) while making space for the merging vehicle compared to risk-averse drivers (M = -0.79 $\mathrm{m/s^2}$), as shown in Fig. 8. Thus, the first hypothesis **(H1)** has been supported. Furthermore, risk-tolerant drivers expected a shorter time gap (M = 1.00 s) when releasing the merging vehicle than risk-averse drivers (M = 1.27 s) as seen in Fig 9. This finding aligns with the second hypothesis **(H2)**, suggesting that drivers with high-risk tolerance expect efficient merging, whereas risk-averse drivers prefer safer merging. In the scenarios where the relative speed between the merging vehicle and the host vehicle is negative, participants applied higher-intensity deceleration (M = -0.72 $\mathrm{m/s^2}$) and releases with shorter gaps (M = 1.07 s) than the scenarios with zero relative speed (M = -0.57 $\mathrm{m/s^2}$, M = 1.22 s).

C. Subjective Evaluation: Risk, Delay, Trust

As shown in Table IV, significant main effects have been observed for risk with respect to the threshold. This indicates that as the decision threshold decreases, the perceived risk values reported by participants increase (0.3 s: M = 4.04, 0.6 s: M = 2.64, 0.9 s: M = 2.10), as depicted in Fig. 10. Regarding delay, significant main effects have been identified for both driving style and threshold.

As illustrated in Fig. 11, risk-tolerant drivers perceive delays more acutely (M = 3.75) than those who are risk-averse (M = 3.09). Additionally, as the decision threshold increases, participants' perceived delay is also heightened (0.3 s: M = 2.72, 0.6 s: M = 3.25, 0.9 s: M = 4.17).

TABLE III

RESULT OF 3-WAY ANOVA: DECELERATION AND EXPECTED MERGING GAP

Parameter	Deceleration			Expected Gap		
	df	F-value	p-value	df	F-value	p-value
Driving Style	1	41.0	**4.9e-10**	1	38.4	**1.6e-09**
Relative Velocity	1	12.4	**4.8e-04**	1	12.6	**4.3e-04**
Criticality	1	0.22	0.63	1	0.07	0.78
Driving Style * Relative Velocity	1	0.22	0.97	1	0.15	0.69
Relative Velocity * Criticality	1	0.22	0.63	1	0.32	0.57
Criticality * Driving Style	1	0.22	0.81	1	3.05	0.08
Driving Style * Relative Velocity * Criticality	1	0.22	0.81	1	1.86	0.17

TABLE IV

RESULT OF 3-WAY ANOVA: PERCEIVED RISK, DELAY AND TRUST

Parameter	Perceived Risk			Perceived Delay			Perceived Trust		
	df	F-value	p-value	df	F-value	p-value	df	F-value	p-value
Driving Style	1	0.01	0.91	1	5.1	**0.025**	1	0.12	0.73
Criticality	1	1.59	0.21	1	1.6	0.21	1	5.0	**0.026**
Threshold	2	14.3	**2.0e-06**	2	8.6	**2.7e-04**	2	3.1	**0.048**
Driving Style * Criticality	1	0.29	0.59	1	0.01	0.90	1	0.01	0.93
Driving Style * Threshold	2	2.40	0.09	2	0.70	0.50	2	7.35	**8.5e-04**
Criticality * Threshold	2	0.03	0.97	2	0.21	0.81	2	0.15	0.86
Driving Style * Criticality * Threshold	2	0.14	0.86	2	0.14	0.86	2	0.32	0.72

Next, the evaluation of trust is considered. Significant main effects have been noted for criticality, and a significant interaction effect between driving style and threshold can be observed. Trust levels decrease (M = 6.14) as the merging vehicle approaches the end of the merging point (M = 6.76), aligning with the previous research [21]. Furthermore, the interaction effect revealed that risk-tolerant drivers exhibited higher trust levels in short-gap merges (0.3: M = 6.75, 0.6: M = 6.64, 0.9: M = 5.76), whereas risk-averse drivers exhibited higher trust levels in long-gap merges (0.3 s: M = 5.42, 0.6 s: M = 7.00, 0.9 s: M = 7.06). This finding supports the third hypothesis **(H3)**, which posits that achieving merges that closely align with expectations effectively maximizes trust.

Finally, to analyze the correlation between subjective evaluation criteria, perceived risk, delay and trust, a multiple correlation analysis has been conducted. Fig. 13 shows a moderate negative correlation between risk and trust, with a correlation coefficient of $r^2 = 0.66$. This finding suggests that as perceived risk decreases, the level of trust increases, which aligns with prior research [7]. Conversely, no significant correlation is observed between perceived delay and trust. This indicates that the varying risk perception based on driving styles, results in different trust evaluations.

Considering these results, we can now discuss the design principles for the automated merging vehicle controller. While the merging vehicle selects a target merging space, it should begin to identify the driving style of the host vehicle based on that vehicle's deceleration profile with respect to its preceding vehicle. Furthermore, the way the host vehicle creates space after the merging vehicle indicates its merging intention can be used to infer its driving style. The merging vehicle should then adapt its decision-making threshold to execute the merge according to the inferred driving style.

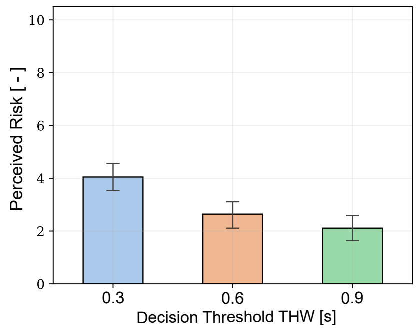

Fig. 10. The subjective scores of risk according to the decision-making threshold (mean and 95% confidence interval)

Specifically, for drivers identified as risk-averse, the merging vehicle should prioritize safety over efficiency by ensuring a sufficiently large gap before initiating the merge. Conversely, for drivers perceived as risk-tolerant, the merging vehicle can execute a more efficient merge with a shorter gap. This approach is designed to maximize trust in automated vehicles from the perspective of other road users.

V. CONCLUSION

This study provides valuable insights for designing a controller for automated vehicles to operate in a merging scenario that requires mutual negotiation with human-driven vehicles. The experimental findings reveal that how space is created for the merging vehicle varies according to the host vehicle's driving style: risk-averse drivers anticipate and trust merging over longer distances, whereas risk-tolerant drivers expect to merge over shorter distances. These findings suggest that adapting the decision-making threshold based on the

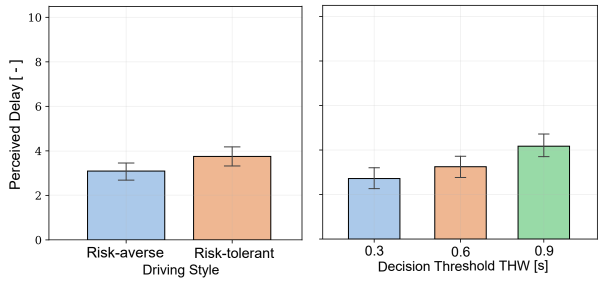

Fig. 11. The subjective scores of delay according to the driving style and the decision-making threshold (mean and 95% confidence interval)

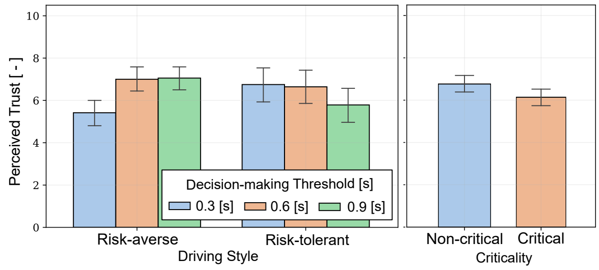

Fig. 12. The subjective scores of trust according to driving style and the criticality of the situation (mean and 95% confidence interval)

host vehicle's driving style could enhance the level of trust perceived by the host vehicle in congested merging scenarios. These results could be leveraged to develop collaborative automated vehicles that improve both safety and efficiency in real-world traffic situations.

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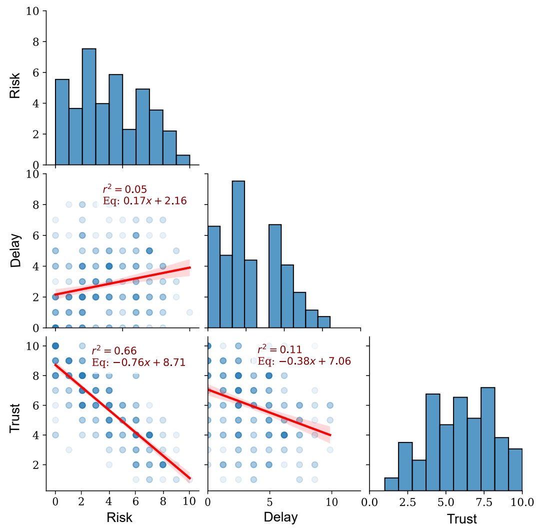

Fig. 13. Correlation analysis of subjective items. The values are the results of the Pearson correlation analysis.

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