HMI Design for Chain-Braking Event Based on V2V Communication

Song Yan

Intelligent Transportation Thrust, The Hong Kong University of Science and Technology (Guangzhou), Guangzhou, China, syan931@connect.hkust-gz.edu.cn

Chunxi Huang

Interdisciplinary Programs Office (IPO), The Hong Kong University of Science and Technology, Hong Kong SAR, China, tracy.huang@connect.ust.hk

Weiyin Xie

Robotics and Autonomous Systems Thrust, The Hong Kong University of Science and Technology (Guangzhou), Guangzhou, China, wxie593@connect.hkust-gz.edu.cn

Dengbo He*

Intelligent Transportation Thrust, The Hong Kong University of Science and Technology (Guangzhou), Guangdong, China

Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Hong Kong SAR, China, dengbohe@ust.hk

Due to the occlusion of front vehicles, in most cases, drivers can only be reactive to the lead vehicle directly ahead of it (DLV) in chain braking scenarios. Research on connected vehicles has suggested that the awareness of traffic flow in chain braking scenarios can improve traffic safety. Thus, in a video simulation experiment, we explored the safety benefits and users' acceptance of two windshield-displayed V2V-communication-based HMIs that inform the chain braking events, one with streaming video from the camera in front of the DLV (vHMI) and the other with warning sign informing chain braking events (sHMI). We found that both HMIs improved drivers' understanding of the situation and reduced reaction time and braking response time (BRT) compared to that of the baseline condition (without HMIs). Further, users reported higher usability and satisfaction with sHMI. This research highlights the benefits of providing front-traffic information to drivers in chain braking scenarios.

CCS CONCEPTS • Human-centered computing • Human computer interaction (HCI) • HCI design and evaluation methods

Additional Keywords and Phrases: V2V Communication, Safety Warning, HUD, Chain-Braking Event

ACM Reference Format:

First Author's Name, Initials, and Last Name, Second Author's Name, Initials, and Last Name, and Third Author's Name, Initials, and Last Name. 2018. The Title of the Paper: ACM Conference Proceedings Manuscript Submission Template: This is the subtitle of the paper, this document both explains and embodies the submission format for authors using Word. In Woodstock '18: ACM Symposium on Neural Gaze Detection, June 03–05, 2018, Woodstock, NY. ACM, New York, NY, USA, 10 pages. NOTE: This block will be automatically generated when manuscripts are processed after acceptance.

---

[*] Corresponding author.

1 INTRODUCTION

Rear-end collision is one of the most frequent types of traffic incidents on road [13]. Among rear-end collisions, the chain-reaction crash is considered to be one of the most dangerous types of road crashes, especially when it occurs at high speed and involves multiple vehicles [16]. The lack of awareness of the leading traffic may worsen drivers' reactions to the chain braking events: when following a chain of vehicles on roads, in most conditions, drivers can only react to the lead vehicle directly ahead of them (DLV) due to the occlusion of front vehicles.

To reduce the risks of rear-end collisions, safety warning systems have been proposed. Various types of sensors have been adopted to detect the surrounding hazards, such as cameras [3, 15], radars [21], and lidars [8]. Based on these sensors, different human-machine interfaces (HMIs), for example, camera-based collision warning system [4] and radar-based collision warning system [23]. However, most warning systems were based on the perception capabilities of the ego-vehicle, which were still limited in terms of the detection range, i.e., these systems were still not able to provide motion information of the vehicles that are out of the line of sight (LOS) [17]. The vehicle-to-vehicle (V2V) communication technologies emerged in recent years may provide promising solutions to this problem [1]. Through V2V communications, drivers can receive real-time information regarding the surrounding vehicles, even when the vehicles are visually occluded.

The safety and efficiency benefits of V2V communication in longitudinal control of the vehicle have been well documented in Connected and Autonomous vehicle (CAV) studies [12, 25]; however, have not been applied to reduce the collision risk in chain braking events. Considering the relatively long deployment cycle of in-vehicle technologies [10, 11], in the foreseeable future, the CAVs will still have to share the road with human-driven vehicles (HDVs). Thus, it would be meaningful to consider a better application of the V2V technologies in HDVs and the V2V-based warning for chain braking events might be one of them. Therefore, this video-simulation study proposes two V2V-based HMIs to provide drivers with leading traffic information in chain-braking events - one with streaming video from the camera in front of the DLV (vHMI) and the other with warning sign informing chain-braking events (sHMI). It is hypothesized that both V2V-based sHMI and vHMI can shorten reaction time and braking response time (BRT) and increase the safety margin in chain braking events, but vHMI might have better effect, given that the dynamic information was found to be more effective compared to static information to the drivers when the hazard is invisible due to occlusions [26].

It should be noted that the experiment presented in this paper is preliminary and aims to validate the concepts of sHMI and vHMI. A follow-up driving simulation study will be conducted based on the results of this video-based study.

2 METHOD

2.1 Participants and Apparatus

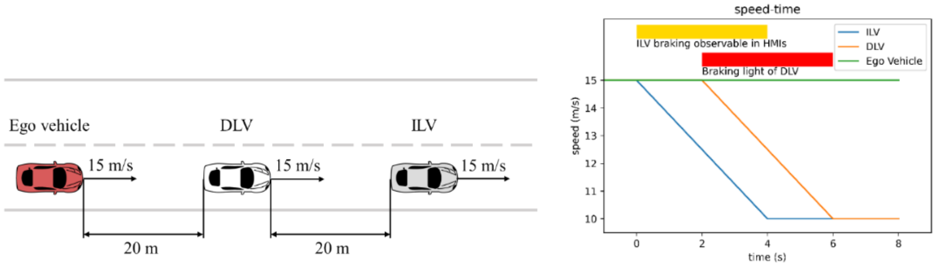
A total of 12 participants (7 male and 5 female) from [Placeholder for Review] with valid driving licenses were recruited for this study. The 12 participants were aged between 22 and 31 years, with a mean of 26 and a standard deviation (SD) of 2.58 years old. Their years of licensure were from 1 to 11 years (mean: 5.42, SD: 2.84). The study was approved by the Human and Artefacts Research Ethics Committee at [Placeholder for Review] ([Placeholder for Review]). The video simulation experiment was conducted on a 27-inch screen with a keyboard (Figure 1).

2.2 Scenario and Driving Task

In this study, we considered a typical three-vehicle chain braking scenario as shown in Figure 2. In the scenario, three vehicles were travelling on a straight rural road, with the ego vehicle following a DLV, and the DLV following an indirect leading vehicle (ILV). The three vehicles had the same initial speed of 15 m/s, and the gap distance between each pair of vehicles was 20 meters at the beginning of the scenario.

a b

Figure 1: The setup for the video simulation experiment: a) screenshot of the driving scenario and the place of participants' hands; b) the apparatus for the experiment.



a b

Figure 2: Chain-braking scenario design: a) Initial condition; b)Speed profile of involved vehicles.

In each drive, the three vehicles traveled at the initial speed for a certain period (hereafter referred to as the normal driving phase) until the ILV started to brake at a predetermined moment (t_0). Three lengths of the normal driving phase (i.e., 10 sec, 20 sec, and 30 sec) were included in the study to prevent drivers from anticipating the moment of the braking event. The acceleration of the ILV in the braking event was -1.25 m/s^2 and lasted for four seconds; after that, the ILV maintained a speed of 10 m/s. To avoid a collision with the ILV, the DLV started to brake 2 seconds after t_0. If no braking behavior of the ego vehicle was performed in the event, the ego vehicle would crash into the DLV 8 seconds after t_0. This chain braking event led to a medium level of urgency for the ego vehicle, according to a previous study that summarized drivers' collision avoidance behaviors on highways [22]. Figure 2b presents the speed profile of the three vehicles in this chain-braking scenario. The chain-braking scenarios were created in Roadrunner, a tool for designing and simulating 3D driving scenarios [19].

During the experiment, participants were required to watch the simulated scenarios and imagine that they were driving the ego vehicle. Their task was to judge the level of urgency in the scenario and indicate the moment they felt it necessary to brake by pressing the space bar on the keyboard (Figure 1a). To eliminate interference from irrelevant factors, participants were required to place their hands on the designated location marked with black squares at the beginning of each drive (Figure 1b) and should always do so until they feel it necessary to move their hands to prepare for the braking.

2.3 HMI Design

Two HMIs were designed and investigated in this study, i.e., the sHMI, and the vHMI. All HMIs were displayed in a heads-up display (HUD) as previous research found that the HUD is less mentally stressful and can reduce drivers' reaction time in urgent situations compared to heads-down displays [14]. Further, the display location was set to be high in the sky to avoid potential visual interference with the road agents in the front view.

Figure 4 illustrates a scenario with sHMI. In the normal driving phase, the sHMI will be absent, and the sHMI will show up when the ILV braked (Figure 3b and 3c). It should be noted that there was a phase (Figure 3c) where both the brake light of the DLV and the sHMI showed up as both vehicles were braking in this period.

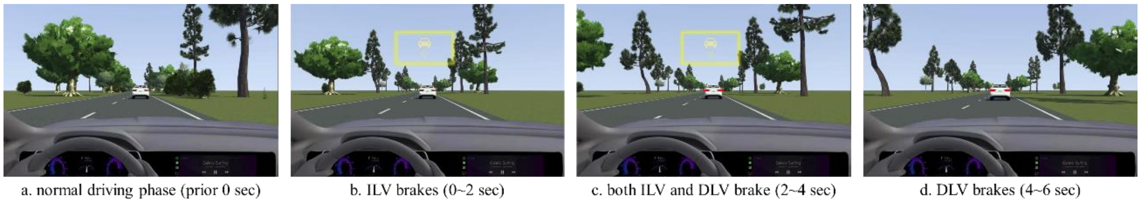

a. normal driving phase (prior 0 sec) b. ILV brakes (0~2 sec) c. both ILV and DLV brake (2~4 sec) d. DLV brakes (4~6 sec)

Figure 3: sHMI with ILV braking information

The vHMI is demonstrated in Figure 4, where the streaming video from the camera in front of DLV is displayed in real-time. As the ILV braked, a warning signal will light up on the boundary of the video display area (Figure 4b and 4c). Compared to the sHMI, the vHMI not only provided the driver with the braking information of DLV, but also provided the real-time motion in depth, which is expected to help the driver better percept the speed of ILV [18].

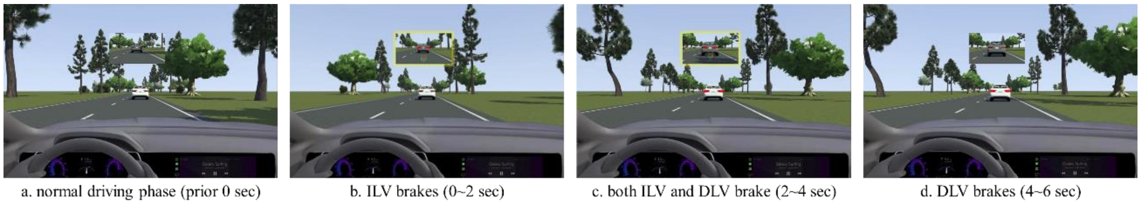

a. normal driving phase (prior 0 sec) b. ILV brakes (0~2 sec) c. both ILV and DLV brake (2~4 sec) d. DLV brakes (4~6 sec)

Figure 4: vHMI with streaming video from DLV

The baseline condition (Figure 5) included no additional HMIs. In this condition, due to the occlusion of DLV, the driver in the ego vehicle was unaware of the motion of ILV.

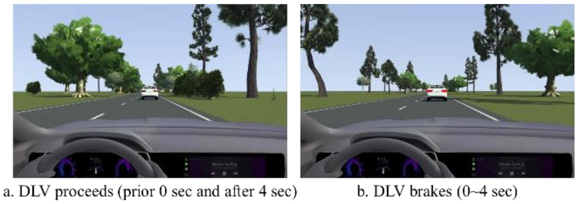

a. DLV proceeds (prior 0 sec and after 4 sec) b. DLV brakes (0~4 sec)

Figure 5: Baseline condition without HMI

2.4 Experiment Design

A within-subjects design was used for this study, with the HMI design (baseline, vHMI, and sHMI) as the only within-subject variable. The order of the HMI conditions was counterbalanced across the 12 participants. Each participant did four drives for each HMI design, including three drives with chain-braking events and one drive without braking. The three drives with chain-braking events had the same settings for chain-braking maneuvers, but the length of the normal driving phase prior to chain-braking was set to 10s, 20s, and 30s, respectively. The order of the four drives within each HMI condition was randomized to prevent the participants from anticipating the timing of the chain-braking event. Thus, we collected data from 144 drives in total (12 participants * 3 HMI designs * 4 drives per HMI design).

2.5 Procedures

Upon arrival, oral consent was obtained from the participant. Then, they completed a pre-questionnaire collecting their demographic information and their driving-related information (i.e., years of licensure and driving mileage in the past one year). Then, they received training on the experiment task, in which the participants received verbal instructions followed by a demo drive without HMI to familiarize them with their tasks. The demo drive included no HMI, but the participants needed to press the space bar to indicate the moment to brake the ego vehicle. Further, to prime participants of the scenario urgency in the experiment, the braking event in the demo drive was set to be urgent with a greater acceleration (-2.5 m/s^2) for both ILV and DLV. The rest elements of the driving scenario in the training session (including the road type and the traffic condition) were consistent with those in the experimental drives.

Next, for each of the three HMI types, the participant completed four experimental drives. Before each HMI condition, participants received written instructions on the meaning of the HMI. After each experimental drive, a subjective questionnaire was administrated, measuring participants' perception of the HMIs, their understanding of the situation, perceived risk [9] and workload in the previous drive (as measured by NASA-Task Load Index [7]), acceptance of the HMI [20], and perceived usability of the HMI [2]. The understanding of the situation was measured using a single question: "*I am fully aware of the motion of front vehicles*" with possible responses ranging from 1 ("I can barely understand it") to 5 ("I fully understand it"). Finally, before the end of the experiment, we asked an open question seeking any comments regarding the HMI designs in the experiment.

2.6 Dependent Variables and Statistical Analysis

Both objective and subjective measures have been collected to evaluate the proposed HMIs. The safety benefits of the HMIs were evaluated through two objective metrics, i.e., reaction time and BRT. The reaction time was defined as the interval between the moment the DLV started to brake and the reaction of the participants (i.e., the moment their hands left the table). The BRT was defined as the interval between the moment the DLV started to brake and the moment the participant pressed the space bar, which was found to be associated with the likelihood of rear-end collisions in chain-braking events [16, 22].

The subjective measures were calculated following the standard procedures for the corresponding questionnaire. The perceived risk was formulated as a ten-point scale ranging from 0 (low risk) to 10 (high risk) [9]. The workload was calculated as a standard NASA TLX score going from 0 (low workload) to 100 (high workload) [7]. Users' acceptance of the HMI included two dimensions, i.e., usefulness and satisfaction, and both ranged between -2 (low) and 2 (high) [20]. The perceived usability was a standard system usability scale (SUS) score ranging from 0 (low) to 100 (high) [2].

All statistical analyses were conducted in SAS OnDemand. A one-way repeated measures ANOVA was performed using the PROC MIXED for reaction time and BRT. The HMI design was used as the only independent variable, and the repeated measures were accounted for with generalized equation estimation (GEE). The Tukey test was used for post-hoc pairwise comparisons if the HMI design was significant ($p < .05$). Further, the Friedman test [6] was used with the HMI design as the independent variable for all other variables due to the small sample size we had. The post-hoc comparisons were conducted using the Students' t-test if the HMI design effect was significant ($p < .05$), as the samples satisfied the assumptions for t-tests.

3 RESULTS

3.1 Reaction Time and BRT

Figure 6 illustrates the distribution of participants' reaction time and BRT in the chain braking events. Both reaction time (F(2, 22) = 45.44, *p* < .0001) and BRT (F(2, 22) = 45.44, *p* < .0001) were significantly different across HMI conditions. Table 1 and Table 2 further illustrate the mean difference (Δ), 95% confidence interval (95%CI), t-value, and p-value for post-hoc pairwise comparisons of reaction time and BRT.

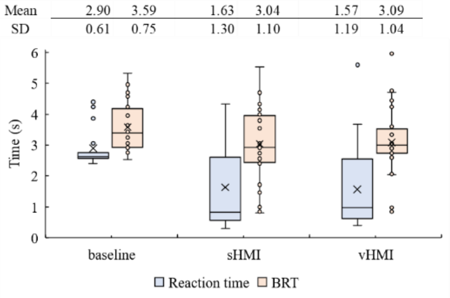


Figure 6: The distribution of reaction time and BRT across three HMI conditions. In this figure and the following figures, boxplots represent the five-number summary, along with the mean depicted through crosses.

Table 1: Pairwise comparisons for reaction time and BRT

	Reaction time			BRT		
	Δ (95%CI)	t-value	*p*	Δ (95%CI)	t-value	*p*
vHMI vs. sHMI	0.02 (-0.2, 0.3)	t(22) = 0.18	.98	0.05 (-0.2, 0.3)	t(22) = 0.47	.9
vHMI vs. baseline	-0.9 (-1.1 -0.6)	t(22) = -8.16	<.0001	-0.5 (-0.7, -0.2)	t(22) = -4.69	<.0001
sHMI vs. baseline	-0.9 (-1.2, -0.6)	t(22) = -8.35	<.0001	-0.5 (-0.8, -0.2)	t(22) = -5.16	<.0001

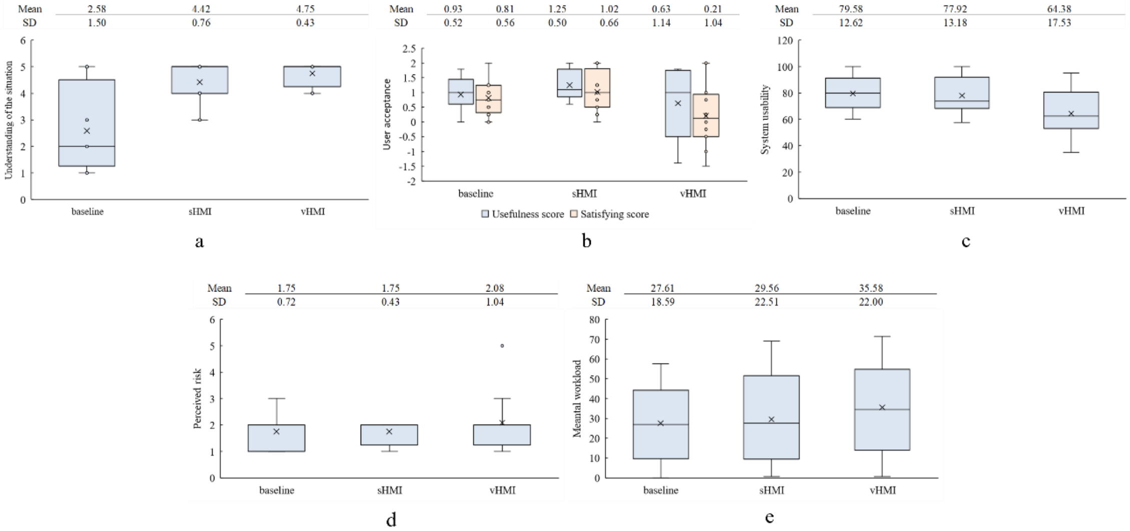


Figure 7: The distribution of subjective metrics: a) participants' understanding of the situation; b) user acceptance scores; c) SUS scores; d) perceived risk; e) mental workload scores.

3.2 Subjective Metrics

As shown in Figure 7, Significant differences between HMI conditions in terms of participants' understanding of the situation (*p* = .0002), satisfying score (*p* = .002) and perceived usability of the HMIs (*p* = .002) have been observed. Other metrics did not meet the significance criteria (usefulness: *p* = .09; perceived risk: *p* = .4; mental workload: *p* = .2). The post-hoc comparisons for significant effects are presented in Table 2.

Table 2: Pairwise comparisons for significant effects

	Understanding of the situation			User satisfying scores			SUS scores		
	Δ (95%CI)	t-value	*p*	Δ (95%CI)	t value	*p*	Δ (95%CI)	t-value	*p*
Baseline vs vHMI	-2.2 (-3.1, -1.2)	t = -4.9	.0005	0.6 (0.0004, 1.0)	t = 2.2	.0499	15.2 (7.0, 23.4)	t = 4.1	.001
Baseline vs sHMI	-1.8 (-2.8, -0.9)	t = -4.3	.001	-0.2 (-0.5, 0.1)	t = -1.5	.2	1. 7 (-6.8, 10.1)	t = 0.4	.7
vHMI vs sHMI	0.3 (0.02, 0.6)	t = 2.3	.04	-0.8 (-1.3, -0.3)	t = -3.6	.004	-13.5 (-20.9, -6.1)	t = -4.0	.002

4 DISCUSSION AND CONCLUSION

In this study, we proposed two windshield-displayed V2V-communication-based HMIs to inform the motion of lead vehicles in chain braking events, one with streaming video from the camera in front of the DLV (vHMI), and the other with warning sign informing chain braking events (sHMI). This study serves as a foundation and can guide more HMI designs that can make better use of the V2V technologies before fully autonomous vehicle saturates the market.

The results show that both the sHMI and vHMI could significantly reduce reaction time and BRT compared to the display in the baseline condition, which can potentially improve driving safety in chain-braking events [22]. Interestingly, there was no significant difference between sHMI and vHMI in terms of their effects on reaction time and BRT, although the vHMI is expected to provide more information regarding the motion of the ILV. It is possible that the vHMI designed in our experiment is too small to be accurately perceived. It is also possible that the scenarios adopted in our study were not complex enough, so the sHMI has provided enough information to drivers. Follow-up driving simulation studies or on-road studies with more complex and dynamic scenarios are needed to further evaluate the two HMI designs.

Further, both sHMI and vHMI were effective in supporting drivers' understanding of the scenario and did not increase the workload of drivers compared to the baseline condition. This suggests that providing additional information about the leading vehicle through HMIs may improve drivers' understanding of the situation in a chain-braking scenario and thus improve their capabilities to respond to potential hazards. However, the participants reported a similar level of perceived risk across the HMI conditions. This is potentially because of the relatively simple scenarios used in the experiment – the scenario is simple enough even without additional displays.

Again, it seems that the vHMI did not provide additional benefits compared to sHMI except for a slight enhancement in drivers' understanding of the situation. What is more interesting is that the participants perceived sHMI as more satisfying and with higher usability compared to vHMI; the vHMI was even perceived as less satisfying and with lower usability compared to the baseline display. It is likely that the driving task is visually demanding already, and the depth information in the vHMI relies on indirect perception [5, 24], which is both visually and cognitively demanding and thus conflicts with the driving task. This is in line with participants' answers to the post-experiment open-ended question, in which 7 out of 12 participants complained that the vHMI led to distractions and sometimes blocked their LOS. Future HMI that can provide depth and motion information through direct perception [5, 24] may bring additional benefits to driving safety without conflicting with the driving task.

Finally, it should be noted that, as a preliminary study, the sample size of this study was relatively small, and due to the constraints of the experimental conditions, a video simulation instead of a driving simulation was adopted. The noninteractive environment in the video simulation cannot fully reveal the complex and unpredictable nature of real-world driving tasks and limits the metrics we could analyze in the study. Thus, the lack of difference in our study may be due to the over-simplified scenarios in our experiment and the inappropriate design used for vHMI. Future work should evaluate more HMI designs in more complex scenarios and, if possible, in on-road studies.

ACKNOWLEDGMENTS

This work was supported by [Placeholder for Review] ([Placeholder for Review]).

REFERENCES

[1] Basheer, H.S. and Bassil, C. 2017. A review of broadcasting safety data in V2V: Weaknesses and requirements. *Ad Hoc Networks*. 65, (Oct. 2017), 13–25. DOI:https://doi.org/10.1016/j.adhoc.2017.07.004.

[2] Brooke, J. 1996. SUS - A quick and dirty usability scale. *Usability evaluation in industry*. 189, 194 (1996), 4–7. DOI:https://doi.org/10.1201/9781498710411-35.

[3] Chen, Y.-L. et al. 2012. A vision-based driver nighttime assistance and surveillance system based on intelligent image sensing techniques and a heterogamous dual-core embedded system architecture. *Sensors*. 12, 3 (2012), 2373–2399. DOI:https://doi.org/10.3390/s120302373.

[4] Dagan, E. et al. 2004. Forward collision warning with a single camera. *IEEE Intelligent Vehicles Symposium, 2004* (Jun. 2004), 37–42.

[5] DeLucia, P.R. 2008. Critical roles for distance, task, and motion in space perception: Initial conceptual framework and practical implications. *Human Factors*. 50, 5 (2008), 811–820. DOI:https://doi.org/10.1518/001872008X312297.

[6] Friedman, M. 1937. The Use of Ranks to Avoid the Assumption of Normality Implicit in the Analysis of Variance. *Journal of the American Statistical Association*. 32, 200 (Dec. 1937), 675–701. DOI:https://doi.org/10.1080/01621459.1937.10503522.

[7] Hart, S.G. and Staveland, L.E. 1988. Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. *Advances in Psychology*. North-Holland. 139–183.

[8] Hartzell, P.J. et al. 2014. Empirical waveform decomposition and radiometric calibration of a terrestrial full-waveform laser scanner. *IEEE Transactions on Geoscience and Remote Sensing*. 53, 1 (2014), 162–172. DOI:https://doi.org/10.1109/TGRS.2014.2320134.

[9] He, D. 2020. *Understanding and Supporting Anticipatory Driving in Automated Vehicles*. University of Toronto.

[10] Highway Loss Data Institute 2022. Predicted availability of safety features on registered vehicles — a 2022 update. *Highway Loss Data Institute Bulletin*. 2, 39 (2022).

[11] Litman, T. 2023. *Autonomous vehicle implementation predictions: Implications for transport planning*. Victoria Transport Policy Institute Victoria, Canada.

[12] Liu, C. et al. 2017. Distributed conflict resolution for connected autonomous vehicles. *IEEE Transactions on Intelligent Vehicles*. 3, 1 (2017), 18–29.

[13] Liu, Q. et al. 2021. Crash comparison of autonomous and conventional vehicles using pre-crash scenario typology. *Accident Analysis & Prevention*. 159, (Sep. 2021), 106281. DOI:https://doi.org/10.1016/j.aap.2021.106281.

[14] Liu, Y.-C. and Wen, M.-H. 2004. Comparison of head-up display (HUD) vs. head-down display (HDD): driving performance of commercial vehicle operators in Taiwan. *International Journal of Human-Computer Studies*. 61, 5 (Nov. 2004), 679–697. DOI:https://doi.org/10.1016/j.ijhcs.2004.06.002.

[15] Llorca, D.F. et al. 2010. Vision-based traffic data collection sensor for automotive applications. *sensors*. 10, 1 (2010), 860–875. DOI:https://doi.org/10.3390/s100100860.

[16] Nagatani, T. 2015. Chain-reaction crash in traffic flow controlled by taillights. *Physica A: Statistical Mechanics and its Applications*. 419, (Feb. 2015), 1–6. DOI:https://doi.org/10.1016/j.physa.2014.10.055.

[17] Rasshofer, R.H. et al. 2011. Influences of weather phenomena on automotive laser radar systems. *Advances in Radio Science*. 9, B.2 (Jul. 2011), 49–60. DOI:https://doi.org/10.5194/ars-9-49-2011.

[18] Regan, D. et al. 1986. Necessary conditions for the perception of motion in depth. *Investigative Ophthalmology & Visual Science*. 27, 4 (Apr. 1986), 584–597.

[19] RoadRunner - MATLAB: *https://www.mathworks.com/products/roadrunner.html*. Accessed: 2023-06-10.

[20] Van Der Laan, J.D. et al. 1997. A simple procedure for the assessment of acceptance of advanced transport telematics. *Transportation Research Part C: Emerging Technologies*. 5, 1 (Feb. 1997), 1–10. DOI:https://doi.org/10.1016/S0968-090X(96)00025-3.

[21] Wang, C.-C. et al. 2003. Ladar-based detection and tracking of moving objects from a ground vehicle at high speeds. *IEEE IV2003 Intelligent Vehicles Symposium. Proceedings (Cat. No. 03TH8683)* (2003), 416–421.

[22] Wang, X. et al. 2016. Drivers' rear end collision avoidance behaviors under different levels of situational urgency. *Transportation Research Part C: Emerging Technologies*. 71, (Oct. 2016), 419–433. DOI:https://doi.org/10.1016/j.trc.2016.08.014.

[23] Werneke, J. et al. 2014. Perfect timing: urgency, not driving situations, influence the best timing to activate warnings. *Human factors*. 56, 2 (2014), 249–259.

[24] Wickens, C.D. et al. 2013. *Engineering psychology and human performance*. Pearson.

[25] Yang, W. et al. 2020. A Forward Collision Warning System Using Driving Intention Recognition of the Front Vehicle and V2V Communication. *IEEE Access*. 8, (2020), 11268–11278. DOI:https://doi.org/10.1109/ACCESS.2020.2963854.

[26] Zhang, J. et al. 2009. Effects of in-vehicle warning information on drivers' decelerating and accelerating behaviors near an arch-shaped intersection. *Accident Analysis & Prevention*. 41, 5 (2009), 948–958.