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Communication Delay Thresholds for Effective Teleoperation in a Mobility System

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Abstract

In this study, we investigate a threshold of communication delay domain in which a human driver controls the mobility system remotely. To investigate the threshold of the communication delay, an intensive experiment varying communication delay from 0 ms to 900 ms was carried out involving 20 human participants. Experimental results show that the teleoperation performance maintained up to 300 ms of communication delay consistently. However, as the delay increases after 300 ms, the performance degradation starts, and the path tracking error increases ($p < 0.001$). Similarly, time analysis results show that teleoperators maintain consistent control up to 300 ms of delay, but have a trend to prioritize destination arrival over safety for delays greater than 400 ms, which is reflected in decreased completion time and increased vehicle speed. In addition, analysis of obstacle collision shows the number of collisions significantly rises after 300 ms. Therefore, careful risk assessment regarding the teleoperation of the mobility system shall be conducted when the observed communication delay reaches up to 300 ms.

Keywords

System Monitoring, Teleoperation, Communication delay, Human factor, Human behavior

Author summary

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Introduction

Recent developments in autonomous navigation technology are considered promising solutions that can liberate humans from tedious tasks such as driving [1–4]. However, not only so-called mature autonomous driving technology cannot guarantee to perform perfectly in all edge case scenarios, but also the rapidly distributed state-of-the-art

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Table 1. Related works regarding teleoperation with various delays, and dependent variables

Reference	Delay	Participants	Target	Dependent variables
[24]	0 ∼ 1000 ms	16	Remote surgical robot	time, motion, error
[25]	300 ∼ 4000 ms	15	Robot arm	time, pressure
[26]	800 ms	37	Multi-purpose vehicle	time, reaction time, error
[27]	0 ∼ 3000 ms	16	Teleoperated robotic units	error, completion time
[28]	50 ∼ 500 ms	20	Rc car	error, completion time
[29]	sensor:∼ 300 ms, video:∼ 600 ms	19	UGV	error, completion time, effort
ours	0,100,200,300,400,500,900 ms	20	Road vehicle	error, completion time, effort, velocity, obstacle hit

technologies may cause even more severe accidents [5]. According to statistics reported by the U.S. National Highway Traffic Safety Administration (NITSA), there have been 736 traffic accidents by autonomous systems in Tesla models alone since 2019 [6]. Further, according to the disengagement report reported by the California State Transportation Agency (CalSTA), and the California Road Traffic Authority, the cases of autonomous driving disengagement are continuously reported and the numbers are growing rapidly due to the growth of the autonomous vehicle market [7]. As a means to compensate for the growing incidents regarding autonomous navigation and driving, a remote teleoperation solution given by a human operator, which controls road-mobility systems, is attracting attention [8, 9].

The performance of the teleoperation can be influenced by two types of communication delays: one is the delay regarding the transmitting control commands, and the other is the receiving delay of sensor values generated from the teleoperated vehicle (e.g. Camera, LiDAR, Radar, etc.) [10]. First, as most of the sensory of the human teleoperator relies on vision information, generally the camera information is considered as the most important information for a human driver [11]. As a countermeasure to compensate for camera delay, much research using predictive display methods has consistently developed video transmission performance over the years and recent achievements now allow expanding teleoperation possible domain by predicting camera image by considering the communication delay [12–15]. Specifically, there has been active research into leveraging machine learning to predict images taking the measured real-time one-way communication delay [12], and a method of making precise predictions through systematic methods through coordinate transformation has also shown significant improvement for reducing the disparity between the teleoperator's perception and the delayed camera image [15]. However, compensating for the communication delay for command values sent by a teleoperator to a teleoperated vehicle is also a critical and challenging problem [16].

When communication delays affect teleoperation commands, the mobility of the vehicle is significantly impaired [17]. This is because communication delays cause asynchronous vehicle movements that are noticeable to teleoperators [18]. This decline in performance tends to become more pronounced at higher speeds, and it has been reported that performance deteriorates seriously from 170 ms when a teleoperator is driving at a speed of 55 ms [19]. In addition, driving performance was evaluated based on driving errors for various delays [20–22]. Accordingly, recent research trends are devising methods to supplement the transmission of control commands by taking communication delay into account [10, 16, 23].

Table 1 shows a summary of studies related to communication delay in teleoperation targeting vehicles, robots, UGVs, etc. Most of the studies evaluate physical parameters against various preset delay values and include ethological studies involving human subjects. However, to the authors' knowledge, studies targeting road vehicles and urban scenarios with different constant communication delays have not yet been reported. In addition, most studies conducted an analysis based on preset delay values and did not compare various delays in the same experimental environment. In this study, an experiment was conducted assuming an urban teleoperation scenario targeting a road

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vehicle, including the communication delay domain included in Table 3. The purpose of the experiment is to determine the acceptable communication delay domain within which teleoperation can be feasibly conducted.

Contributions

The contributions of this study are as follows.

- Found acceptable communication delay domain in tested scenario (From 300 ms the teleoperation performance decreases)
- Based on the Kruskal-Wallis test, it was found that tracking error and completion time had significant differences against different delayed conditions
- It was found that the driving experience affects the stability of steering control during teleoperation according to the amount of communication delay induced
- We found that the driver's experience has an impact in domains with small communication delays. However, in domains where the vehicle is out of control due to large communication delays, the driver's experience is irrelevant.

Methodology

In this section, methods and virtual experimental environments are briefly explained. The purpose of the presented methodologies is to investigate the effect of the communication delay against the teleoperator's driving control in teleoperation driving.

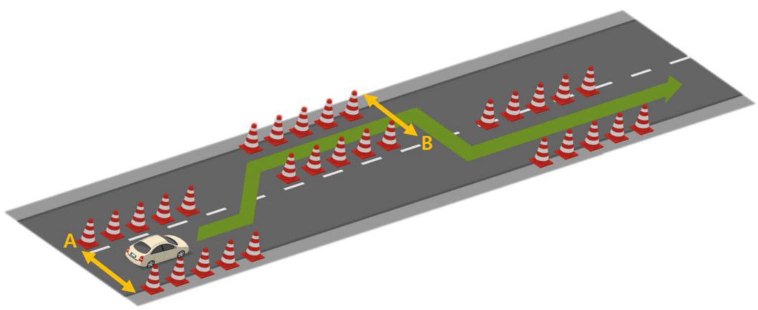

Fig 1. Double lane change. Schematic diagram showing a double lane change scenario track (ISO 3888-1) in a virtual experimental environment. Ten safety cones are placed for each straight section. The total number of safety cones was thirty. A is the start of the first straight section, and B is the end of the second straight section. (This figure was generated with icograms [https://icograms.com])

The virtual experimental environment was built referring to a double lane change track (Fig. 1, straight - lane change - straight - lane change - straight [30]). The reason for choosing the double lane change track was that it involves complex maneuvering and dynamic driver behavior and decision-making.

Safety cones were positioned at regular intervals along both sides of the road for each straight section. The safety cones were not only treated as obstacles that the teleoperator should avoid but also provided guidance for the track. Also, by utilizing the safety cone's coordinates, Reference Center Position (RCP)s are created (Fig. 2). The RCP is a reference point for the comparison between the driver's samples of the driving

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path. It should be noted that the RCPs were generated by interpolating the center position of the safety cones such as [23]:

$$(x_{\mathrm{C}_n}, y_{\mathrm{C}_n}) = (\frac{x_{\mathrm{S}_n} + x_{\mathrm{S'}_n}}{2}, \frac{y_{\mathrm{S}_n} + y_{\mathrm{S'}_n}}{2}), \quad (1)$$

where
x_{C_n}, y_{C_n}: The center point between two safety cones with the same number n
x_{S_n}, y_{S_n}: The position of the upside safety cone number n
$x_{\mathrm{S'}_n}$, $y_{\mathrm{S'}_n}$: The position of the downside safety cone number n

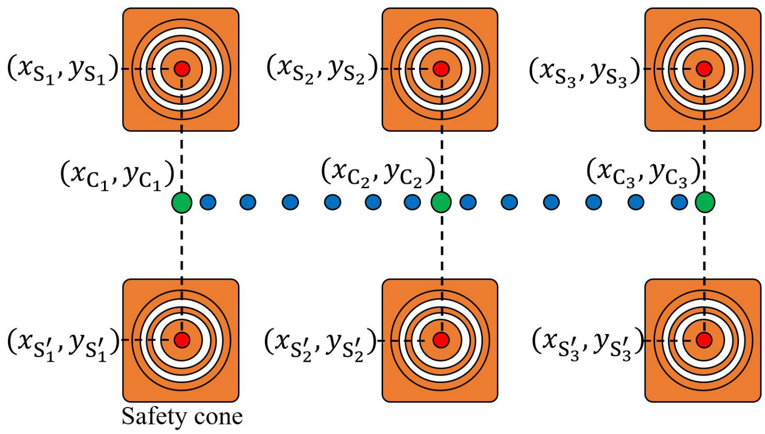

Fig 2. Red points represent the position of safety cones. The $(x_{\mathrm{S}_n}, y_{\mathrm{S}_n})$ and $(x_{\mathrm{S'}_n}, y_{\mathrm{S'}_n})$ are respectively the position of the upside safety cone and downside safety cone number n. The green points are the position of center points$(x_{\mathrm{C}}, y_{\mathrm{C}})$. The blue points are generated using linear interpolation for the center points.

Interpolation points were generated at constant intervals between the center points using linear interpolation. Through configuring scenarios with various communication delay values in the virtual experimental environment, the following samples are obtained: Effort, Error, Cone, and Velocity.

Effort is the accumulated value of steering angle (radian) that teleoperators control steering while driving.

Error is the accumulated value of the distance difference between the center point of the vehicle and the closest RCP point every time step: 0.01 seconds (Fig. 3). In short, the Error value is the sum of the η (in Fig. 3). The η is obtained by the Euclidean Distance and unit is millimeters (mm).

Cone means the sum of the count that teleoperators invade the safety cone during driving.

Velocity is the average velocity of the teleoperator's driving in each scenario.

The teleoperators completed the double lane change track to the end, but the above samples were obtained in section A through section B as shown Fig. 1.

Using the samples and equation (2), we will analyze the effect of communication delay against the teleoperator's driving control in teleoperation driving [29]:

$$P_{\mathrm{comb}} := 0.5\frac{Time_{\mathrm{avg}}}{Time_{\mathrm{t.avg}}} + 0.5\frac{Error_{\mathrm{avg}}}{Error_{\mathrm{t.avg}}}, \quad (2)$$

where

P_{comb} :
Values to indicate the correlation between the driver's driving skills and performance

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$Time_{\mathrm{avg}}$: Average driving time by each value of communication delay (0∽900 ms)
$Time_{\mathrm{t.avg}}$: Total Average driving time of all participants
$Error_{\mathrm{avg}}$: Average driving error by each value of communication delay (0∽900 ms)
$Error_{\mathrm{t.avg}}$: Total Average driving error of all participants

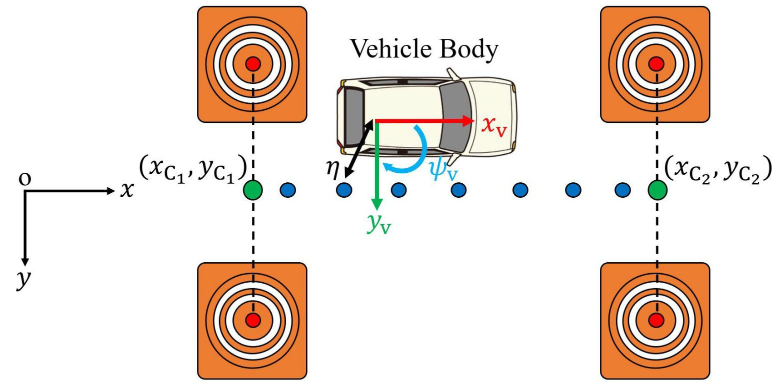

Fig 3. A Vehicle body coordinate system follows SAE standards (3DOF - x_{v}, y_{v}, ψ_{v}). A center point of the Vehicle Body is the center position of the rear axle. η means the distance between the center point of the Vehicle Body and the nearest RCP point. The distance is calculated as Euclidian distance and is measured in millimeters (mm).

Experimental setup

In this section, we introduce an experimental setup and procedure.

0.1 General setup

To investigate the impact of delays in teleoperation driving on teleoperator manipulation, a virtual teleoperation driving environment was constructed using Matlab vehicle dynamics (R2019 a, Mathworks). The virtual driving simulation environment included seven delay values scenarios: 0 ms, 100 ms, 200 ms, 300 ms, 400 ms, 500 ms, and 900 ms. Also, Matlab was utilized for gathering teleoperation driving samples, for instance, steering, throttle, brake, and vehicle location values in the framework of the vehicle dynamics block set. Fig. 4 shows a track of a virtual driving environment. There is a double lane change track (straight - course change – straight - course change - straight). Ten safety cones are placed for each straight section (total cones: 30). To prevent extreme low-speed driving, we set a 60-second time limit on the experimental environment. To control the virtual driving simulation, a wheel joystick (G29, Logitech, Swiss) was used for steering, throttle, and brake control (Fig. 5).

0.2 Participants

We carefully estimated the number of participants based on one-way ANOVA power analysis using G* power software [31], and relevant computations of the required sample size are listed in Table 2. Based on the fact that the average sample size for 1 scenario per 20 participants is estimated as 2,557 which is greater than the required sample size (2,093) A total of 20 participants (14 men and 6 women) joined in this experiment. The number of participants in their 20s was thirteen, and the number of participants in their 30s was seven. Participants were employees of the Korea Institute of Industrial Technology (KITECH) and people who had seen an announcement of the experimental post. As for the selection criteria, we selected people who have a driver's license and

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Fig 4. The teleoperators drove while looking at the display of the experimental environment built using MATLAB vehicle dynamics.

Fig 5. Driving Simulator.
The experiments were conducted using a simulator (G29, Logitech, Swiss)

who have no difficulty driving. Participants were classified into three groups according to their driving experience: A, B, and C. Group A consisted of participants with 1 to 4 years of driving experience, Group B had 5 to 9 years of driving experience, and Group C had more than 10 years of driving experience. It respectively consisted of ten, six, and four people.

0.3 Experimental procedure

Firstly, participants were informed about the purpose of the study and the purpose of using the samples acquired through the experiment before the start of the experiment. And, the participants were introduced to the experimental conditions and procedures, which were approved by Institutional Review Board (IRB, Approval number:

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Table 2. Parameter list for computation of required sample size, where α is a significance level, N is the number of groups, and S_r is the required sample size

Parameter	Value
Effect size	0.1
α	0.05
$1-\beta$	0.95
N	7
S_r	2,093

A-2023-010) for human participation experiments. The experiment was conducted after receiving documents of consent from the participants. Each participant operated the teleoperation driving simulator on a double lane change track (Fig. 4) built in the Matlab vehicle dynamics environment. In each scenario, the participants were asked to control the brake, throttle, and steering to reach the target location without invading the safety cones.

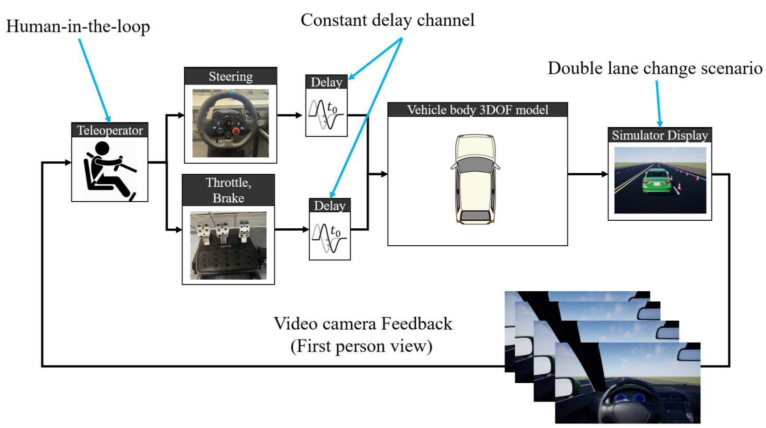

Fig 6. Schematic diagram showing a vehicle control loop in a virtual teleoperation driving environment. The teleoperator inputs the values by operating the steering, throttle, and brake. These input values were affected by a certain delay that is specified. The delayed values were input into the vehicle model and reflected in the simulator display. Then the teleoperator received feedback on the frames of this display.

All participants repeated the experiment 5 sets for each scenario. As a result, a total of 700 driving samples were obtained from 20 participants (5 sets $\times$ 7 scenarios $\times$ 20 people). From the steering, throttle, and brake values operated by the teleoperators, the effort, error, cone, and velocity values were obtained. These values were obtained in section A through section B as shown in Fig. 1

0.4 Analysis of variance

In this study, statistical analyses were performed to assess the significance of differences among multiple groups using one-way analysis of variance (ANOVA). The ANOVA was employed to determine if there were any statistically significant variations in the means of the groups. Subsequently, to identify specific group differences, Dwass-Steel-Critchlow-Fligner (DSCF) pairwise comparisons were conducted as a posthoc analysis.

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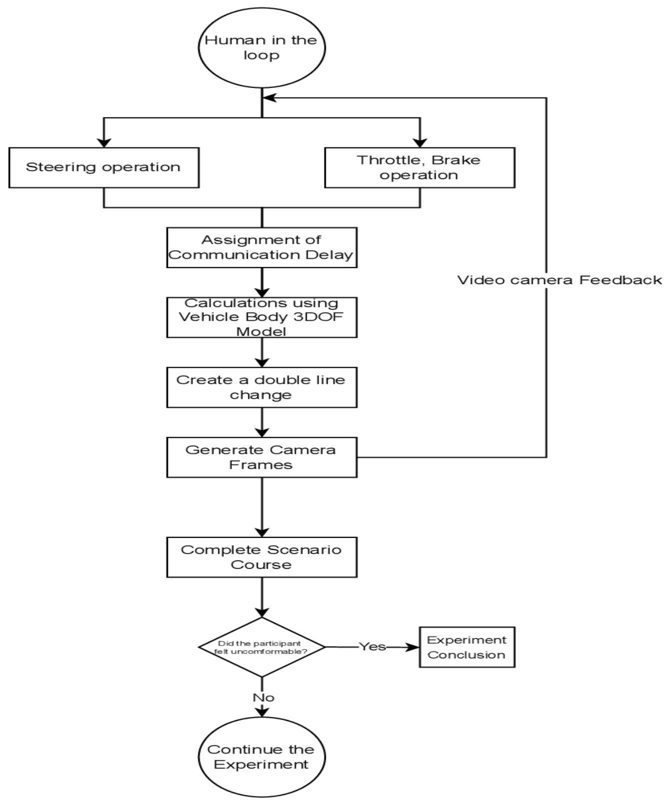

Fig 7. Schematic diagram of the experimental protocol. Blocks for obtaining driving data from the research subject are shown. If the research subject's understanding of the simulator is insufficient, the experiment will be stopped immediately.

0.5 Institutional Review Board

This study was conducted with approval from the Institutional Review Board (IRB, Approval number: A-2023-010). Experiment participants were recruited through a recruitment statement from July 31, 2023, to December 31, 2023. There were no minors among the experiment participants, the experiment was explained to them before the experiment, and they were informed that there would be no disadvantage if they expressed their intention to give up during the experiment. Additionally, consent forms for participation in the experiment were obtained from the participants.

Results

In this section, the results of the experiment described in the methodology are presented. It should be noted that the experiments were divided into groups according to the driving experiences of participants. Results are displayed in bar chart, histogram, and box chart formats.

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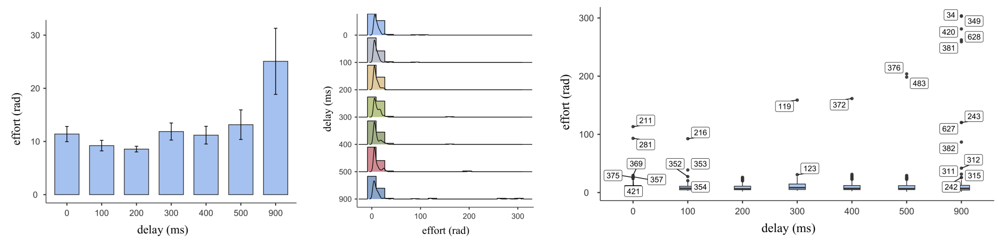

Fig 8. Effort analysis according to different communication delays.

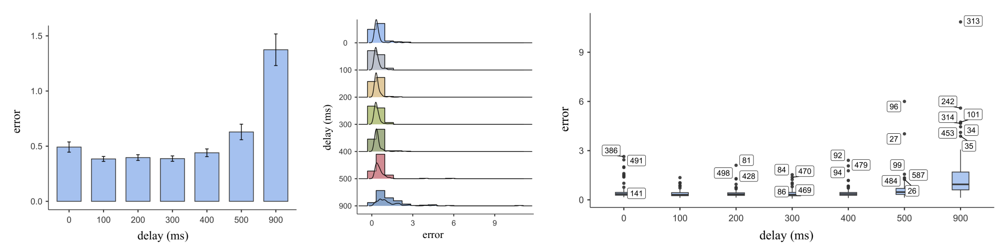

Fig 9. Error analysis according to different communication delays.

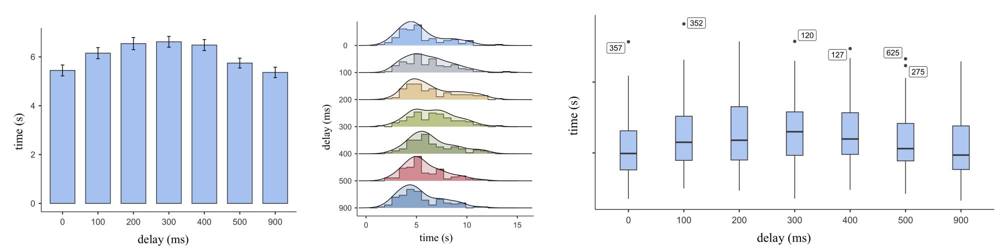

Fig 10. Complete time analysis according to different communication delays.

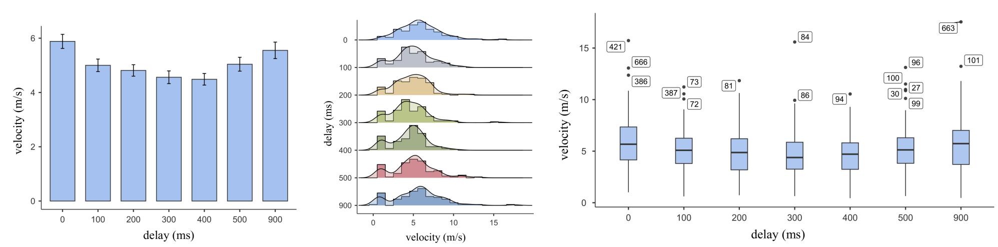

Fig 11. Velocity analysis according to different communication delays.

0.6 Participant's driving samples based on the delays

This subsection shows the driving data of 20 experimenters by the size of the delay. Fig. 8 - Fig. 12 shows the results for effort, error, time, velocity, and obstacle heat counts in bar charts, histograms, and box charts. The effort is the cumulative value of the steering angle, the error is the accumulated value of the distance between the vehicle center point and the RCP, time is the time to pass through the scenario track, velocity is the speed when passing through the scenario track, and the cone is the number of cone hits when traveling on the scenario track.

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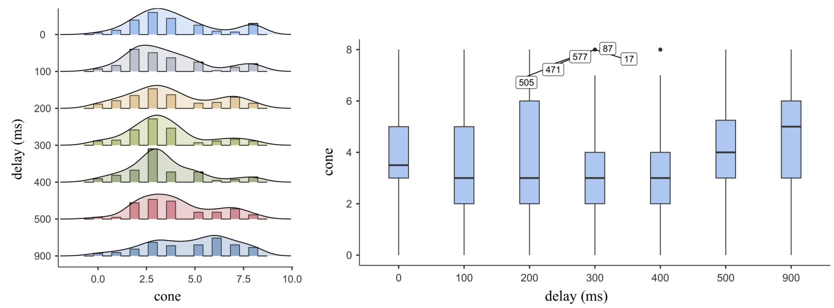

Fig 12. Obstacle hit analysis according to different communication delays.

0.7 Driving samples of participants grouped according to their driving experience.

In this section, groups were classified by the participant's driving experience. Group A classified the driving experience as one to four years (ten people), group B classified as five to nine years (six people), and group C was more than ten years (four people).

0.8 Correlation between the driver's skill and performance

Table 3. The correlation between the skill and performance of all participants

Delay (ms)	Time (s)	Error (mm)	P_{comb}
0 ms	5.44	0.27	0.78
100 ms	6.15	0.24	0.80
200 ms	6.61	0.26	0.86
300 ms	6.61	0.26	0.87
400 ms	6.48	0.32	0.93
500 ms	5.74	0.43	1.01
900 ms	3.36	0.99	1.68

This subsection uses equation 2 to show how the communication delay affects teleoperation. Table 3 shows the driving samples of all participants. Table 4 shows the driving samples of participants in each group.

0.9 ANOVA TEST

Table 5 shows the results of the Kruskal-Wallis test for the driving samples of all participants. X^2 stands for the Kruskal-Wallis statistic. df(degrees of freedom) was used

Table 4. Correlation between driver skills and performance categorized into groups

	group A			group B			group C		
delay	time	error	P_{comb}	time	error	P_{comb}	time	error	P_{comb}
0 ms	4.57	0.30	0.77	6.20	0.26	0.81	6.45	0.19	0.74
100 ms	5.38	0.27	0.81	6.79	0.24	0.84	7.10	0.16	0.75
200 ms	5.82	0.24	0.79	7.33	0.31	0.97	7.15	0.22	0.84
300 ms	6.7	0.22	0.86	6.16	0.32	0.89	7.06	0.25	0.87
400 ms	6.39	0.29	0.92	6.13	0.42	1.01	7.22	0.24	0.87
500 ms	5.24	0.45	1.01	5.52	0.44	0.99	7.34	0.37	1.06
900 ms	5.12	1.11	0.98	5.75	0.78	1.43	5.38	1.04	1.88

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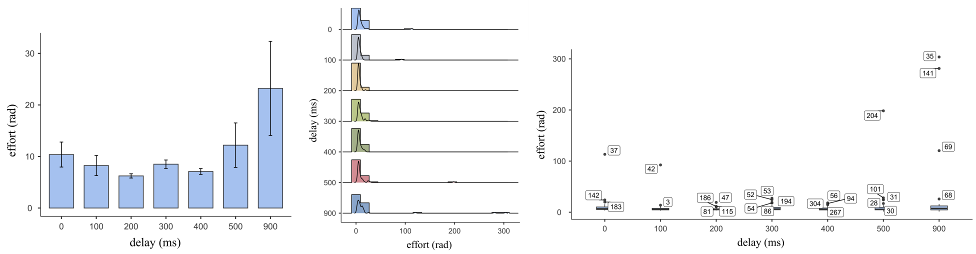
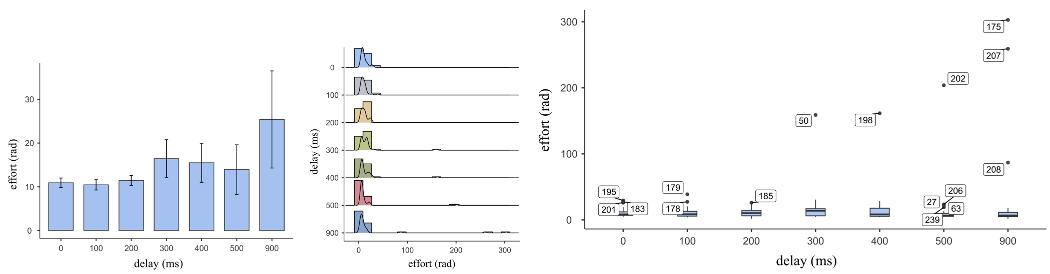
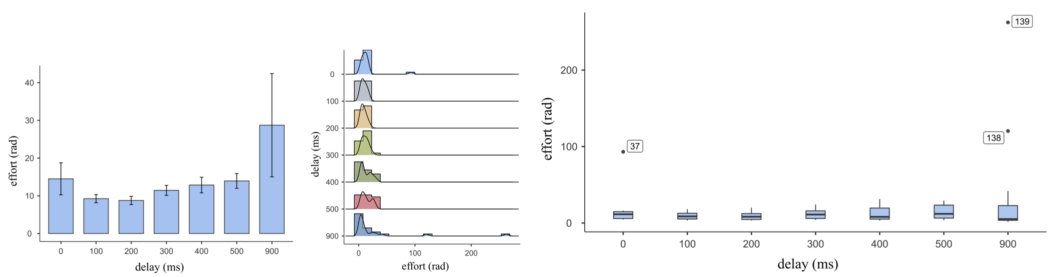


(a) Effort analysis according to different communication delays in group A (experience 1 year - 4 year)



(b) Effort analysis according to different communication delays in group B (experience 5 year - 9 year)



(c) Effort analysis according to different communication delays in group C (more than ten year)

Fig 13. Effort according to the size of the delay extracted by the group.

Table 5. Kruskal-Wallis test

	X^2	df	p
error	209.0	6	< .001
effort	11.1	6	0.086
time	36.3	6	< .001

Table 6. Dwass-Steel-Critchlow-Fligner (DSCF) Pairwise Comparison for Logerror

	100	200	300	400	500	900
0	0.989	0.994	1	0.485	< .001	< .001
100		0.766	1	0.125	< .001	< .001
200			0.977	0.834	< .001	< .001
300				0.44	< .001	< .001
400					0.006	< .001
500						< .001

*:p <0.05,**:p <0.01,***:p <0.001.

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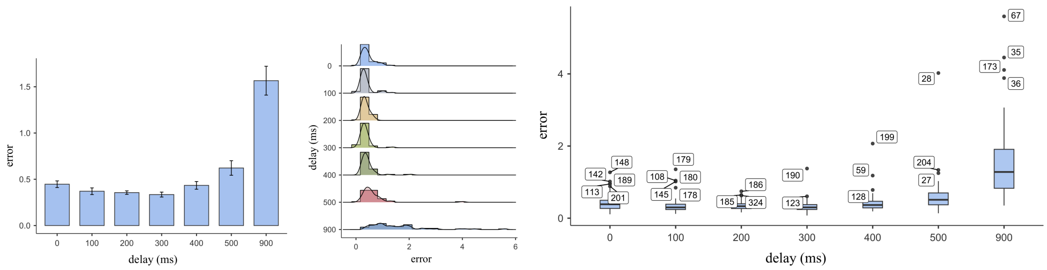
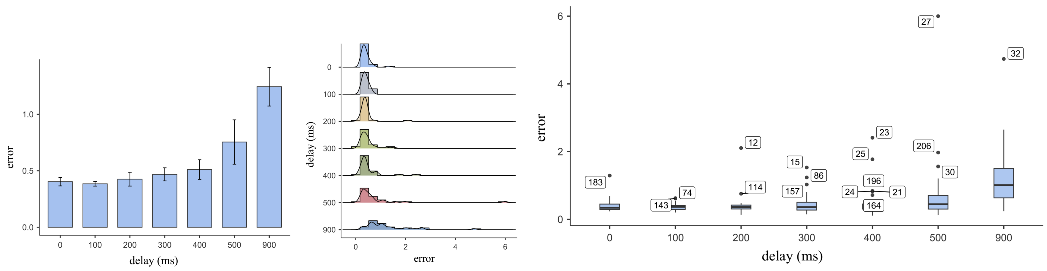
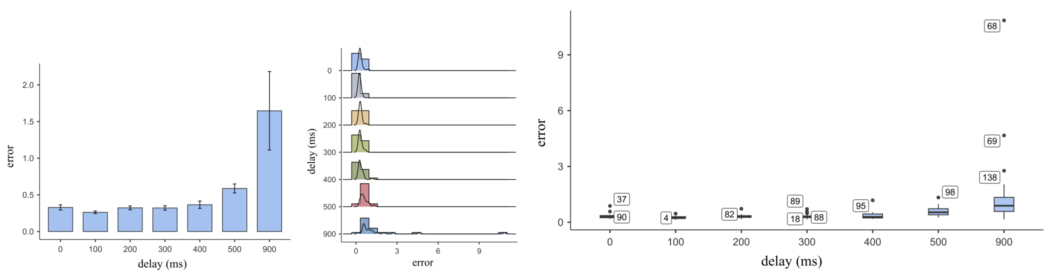


(a) Error analysis according to different communication delays in group A (experience 1 year - 4 year)



(b) Error analysis according to different communication delays in group B (experience 5 year - 9 year)



(c) Error analysis according to different communication delays in group C (more than ten year)

Fig 14. Error according to the size of the delay extracted by the group.

to determine the distribution of test statistics as a degree of freedom. p was used for statistically significant differences between groups.

0.10 Comparison by Dwass-Steel-Critchlow-Fligner (DSCF) Pair with Log Transformation.

Table 6 shows Dwass-Steel-Critchlow-Fligner (DSCF) pairwise comparison results for the driving samples of all participants. The Kruskal-Wallis test assumes that the variance of rankings among groups is different, and based on this, it tests the difference in median values in the population of each group. In addition, log transformation was applied to the acquired sample to transform the distribution of the sample to improve normality. Log transformation was used especially when the distribution or variance with a long tail to the right is abnormally large.

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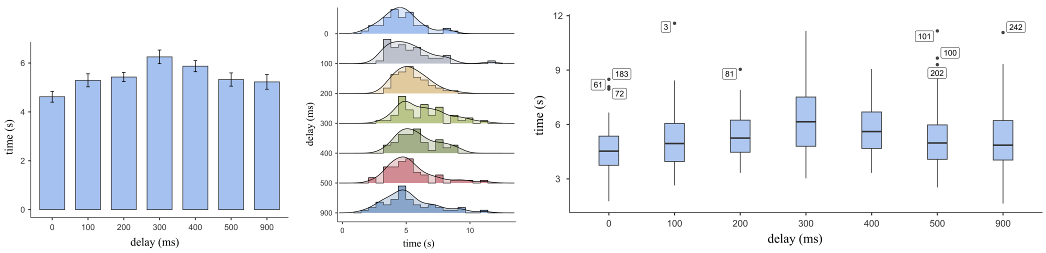
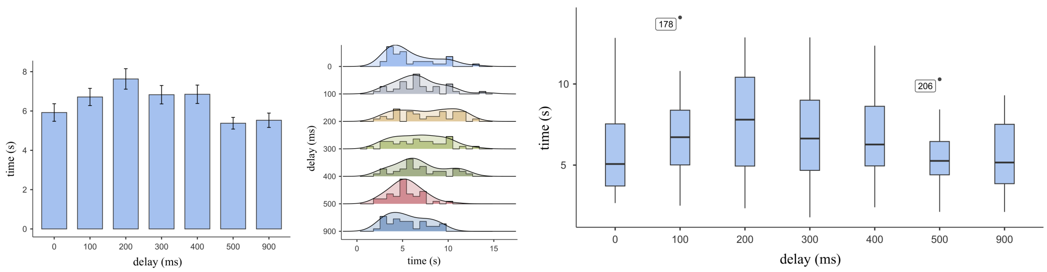
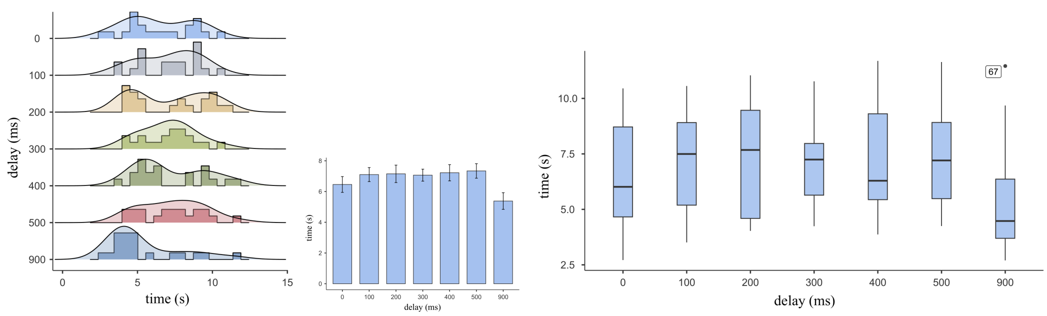


(a) Complete time analysis according to different communication delays in group A (experience 1 year - 4 year)



(b) Complete time analysis according to different communication delays in group B (experience 5 year - 9 year)



(c) Complete time analysis according to different communication delays in group C (more than ten year)

Fig 15. Complete time according to the size of the delay extracted by the group.

Discussions

0.11 Effort analysis

Fig. 8 shows effort analysis for different communication delays. From 0 ms to 200 ms, the effort value decreases, and from 400 ms, the effort value increases. It can be interpreted that, from 0 ms to 200 ms, it seems the teleoperator conducted passive maneuvering due to the induced delay with minimal effort. In addition, from 300 ms to 500 ms, there was no significant difference. However, the total amount of effort increased, which can be interpreted as active maneuvering in order to recover the orientation of the vehicle. Finally, from 900 ms, the vehicle was out of control, and therefore the total amount of effort dramatically increased.

0.12 Error analysis

Fig. 9, shows error analysis for different communication delays. The error values are similar from 0 ms to 300 ms, and the error values start to increase from 400 ms. Fig. 18 shows the analysis result of the log-transformed error and the samples were tested using

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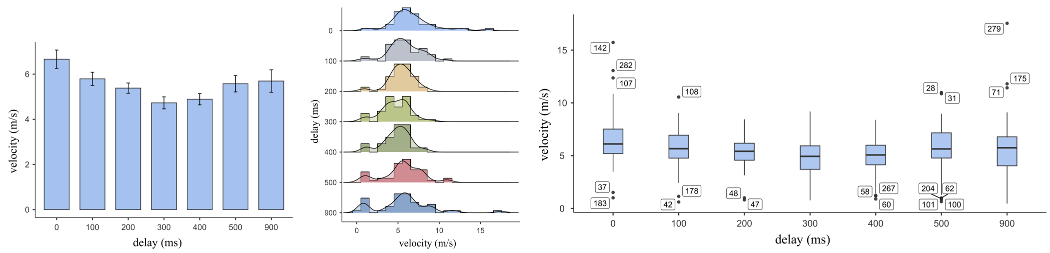
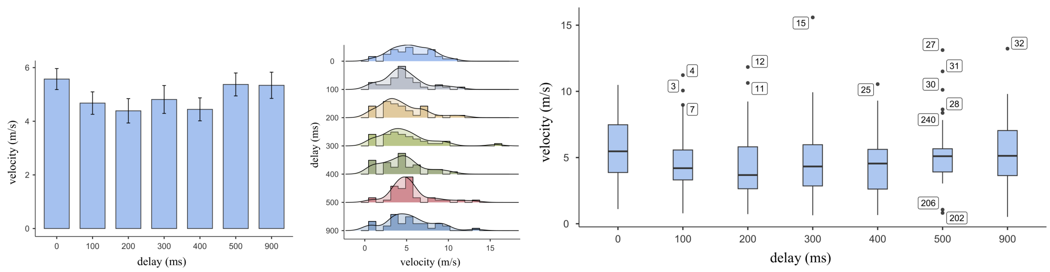
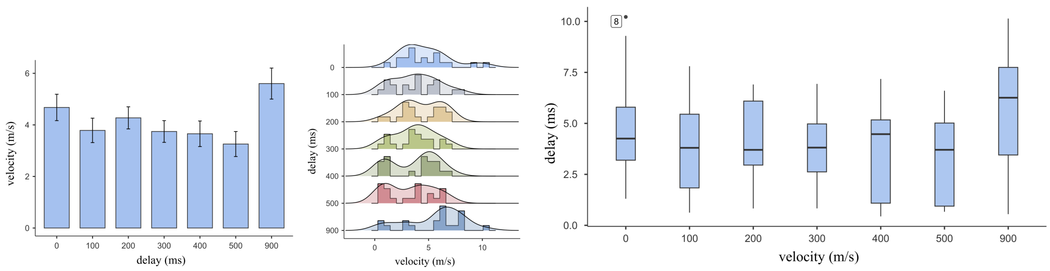


(a) Velocity analysis according to different communication delays in group A (experience 1 year - 4 year)



(b) Velocity analysis according to different communication delays in group B (experience 5 year - 9 year)



(c) Velocity analysis according to different communication delays in group C (more than ten year)

Fig 16. Velocity according to the size of the delay extracted by the group.

ANOVA. When looking at the p-value in Table 6, 0 ms to 500 ms and 900 ms were significant differences ($p < 0.001$). Samples between 100 ms, 200 ms, 300 ms and 0 ms did not show any significant difference (Fig. 18). However, the degradation of the p-value was observed from 300 ms to 400 ms ($p = 0.485$). In other words, although the significance was observed from 400 ms, the error degradation may be starting between 300 ms and 400 ms. Hence, we can conclude that communication delays up to 300 ms should be allowed due to the communication delay in terms of error performance.

0.13 Time analysis

Fig. 10 shows a complete time analysis of different communication delays. It shows an increase from 0 ms to 300 ms. In the delay domain of 0 ms to 300 ms, it seems that participants expend significant time in order to maintain the stability of their driving, believing this period to still be within their capability to drive. From 400 to 900 ms, the completion time is gradually decreasing. This suggests that, once they reach an uncontrollable level of delay, drivers prioritize reaching their destination over safely navigating the track.

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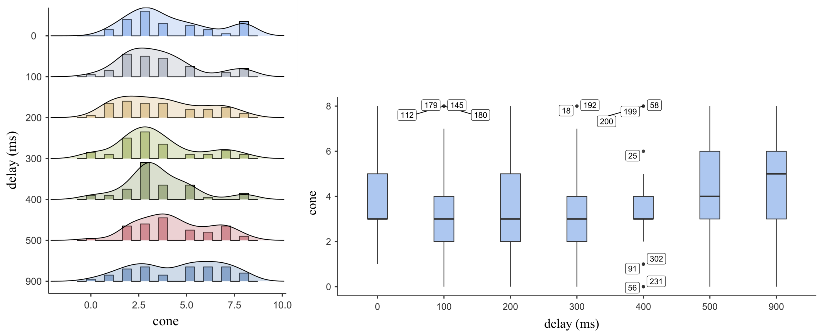
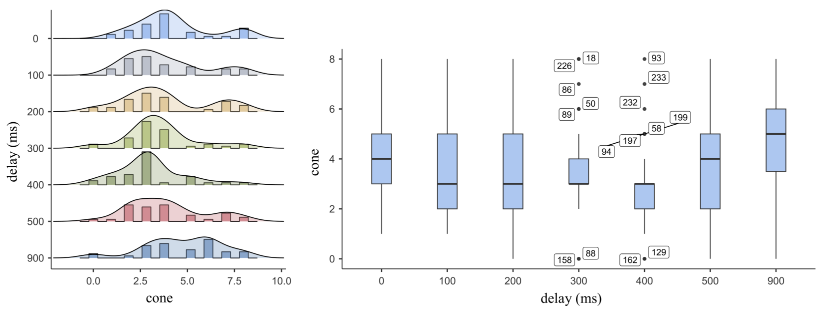
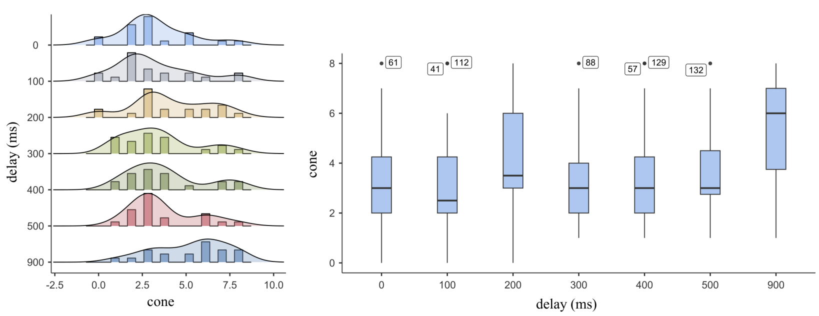


(a) Obstacle hit analysis according to different communication delays in group A (experience 1 year - 4 year)



(b) Obstacle hit analysis according to different communication delays in group B (experience 5 year - 9 year)



(c) Obstacle hit analysis according to different communication delays in group C (more than ten year)

Fig 17. The number of invaded safety cones while driving a vehicle in the experimental environment with constant communication delay. Cone value means the total number of times the teleoperator had hit the safety cones while driving within a particular section. The section referred to A through B is shown in Fig. 1

0.14 Velocity analysis

Fig. 11 shows a velocity analysis of different communication delays. From 0 ms to 400 ms, the speed of the vehicle is decreasing. The driver can control the vehicle, so it appears to be trying to pass the track safely without hitting the obstacles. In the 500 ms to 900 ms domain, the speed of the vehicle increases, and as previously stated, the goal seems to be to quickly move the vehicle to the point of arrival not the safe navigation of the track.

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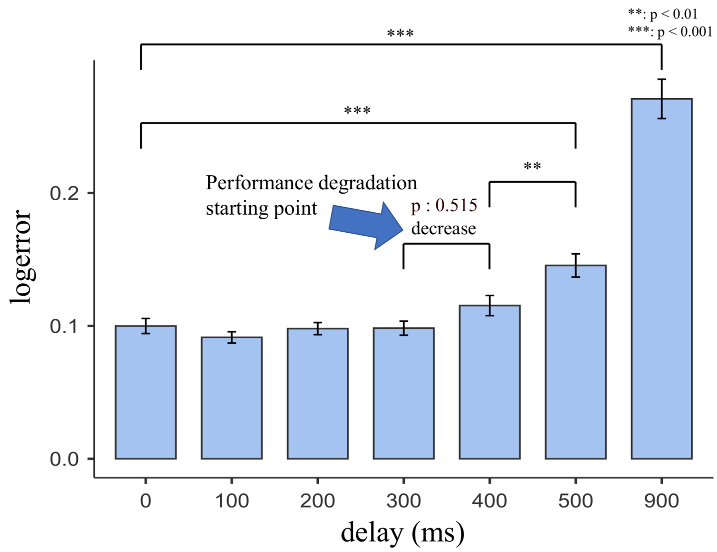

Fig 18. Error samples from drivers with log transformation.

0.15 obstacles hit analysis

Fig. 12, shows an obstacle hit analysis according to different communication delays. It seems that the obstacle has been hit overall, but the domain to be noted is 900 ms where the most hits were made. In addition, the number of obstacles hit was not large in the domain with high communication delays between 500 and 900 ms, and this is because the cone installed on the track was not even close or hit but the vehicle completely left the track.

0.16 Driving samples of participants grouped according to their driving experience.

Fig. 13 shows the analysis of the effect of the group classified according to the driving experience. In Group A, the value of effort is generally low at 0 ms to 400 ms. At 500 ms to 900 ms, the effort appears large. In Group B, it appears constant from 0 to 200 ms. It increases in 300 ms and then increases significantly in the 900 ms domain. In group C, it is constant from 0 ms to 500 ms and then increases significantly from 900 ms. Overall, it appears to be a significant increase from 500 to 900 ms. What should be highlighted is, that the number of outliers among the effort samples was increased in the order of a, b, and c. This indicates that the driving experience affects the stability of steering control during teleoperation according to the amount of communication delay induced.

Fig. 14 shows the analysis of errors by group. In the error analysis results of groups A and B, it gradually increases from 0 to 400 ms, and then increases significantly from 500 ms. group C shows a small overall error but a gradual increase. Overall, increased communication delays increase errors, which means that the driver's career has some impact in areas with small communication delays, but in areas where the vehicle is out of control, the driver's career or technology cannot be free from communication delays.

Fig. 15 shows the analysis of completion time for each group. For group A, the completion time increases from 0 to 300 ms and decreases thereafter. In Group B, completion time increases from 0 to 200 ms, and thereafter, completion time decreases. Group C has a constant completion time from 0 to 500 ms and decreases sharply from 900 ms. Analyzing the overall completion time for groups A, B, and C increases the

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transmission time in domains with low communication delay and decreases the transmission time in domains with high communication delay. At a controllable level, the driver appears to use a lot of time to safely pass through the track, and in domains that are difficult to control, they rather give up.

Fig. 19 shows the vehicle speed analysis by group. Group A decreases in speed from 0 to 300 ms and then increases thereafter. Group B shows a decrease in speed from 0 to 400 ms and then increases from 500 ms. In group C, the speed decreases from 500 ms, and increases rapidly from 900 ms. Rather than in groups A and B, skilled group C is slower to pass the track safely. It should be noted that contrary to expectations, groups A, B, and C all drive at a high speed at 900 ms in common, but the driver seems to give up as vehicle control becomes difficult.

Fig.20 shows the analysis results of obstacle hits by the group. Overall, the number of obstacle hits is evenly distributed. One thing to note is that it was thought that more obstacle hits would be made in areas with large communication delays, but the small number of times does not seem to have been counted because it could not get close to the track and could not hit the obstacle.

0.17 Comprehensive discussion of communication delay

During teleoperation, it is anticipated that greater communication delays will result in larger errors. This correlation was validated by the experimental findings, which demonstrated that as communication delays increased, so did errors.

This study aimed to assess the permissible communication delay and identify the regions where performance degradation occurs. Notably, performance degradation was observed between 300 ms and 400 ms, placing significant strain on the driver. Furthermore, when considering groups segmented by driving experience, errors were more pronounced in areas with prolonged communication delays. This highlights the inability of driver experience and skill to compensate for communication delays.

However, the study yielded unexpected findings. While greater communication delays were expected to necessitate slower vehicle control, drivers appeared to reach a threshold where control became unfeasible, leading them to disengage from driving altogether.

It's important to note that our experiments were simulation-based, and real-world teleoperation scenarios were not tested. Nonetheless, human responses to existing communication delays differed from our assumptions. Addressing teleoperation challenges in environments with communication delays is imperative due to the associated safety risks and the lack of strategies for mitigation by drivers.

0.18 Analysis of gait driving data according to delay size

Fig.19 shows utilized to visualize the periodic driving patterns or maneuvers under various levels of communication delay. This visualization allows us to observe how the driver adjusts their steering input as communication delays increase. In Figures (a) to (c), no significant differences are observed, indicating that steering input variations are minimal under low communication delays. However, in Figure (d), with a communication delay of 400 ms, there is a noticeable increase in steering input, accompanied by cone collisions.

Additionally, as seen in Figure (d) with a 400 ms delay, obstacle invasions begin when passing through sections 2 and 4, with the frequency of cone collisions increasing as the delay grows. This suggests that performance degradation due to communication delay begins around 300 ms.

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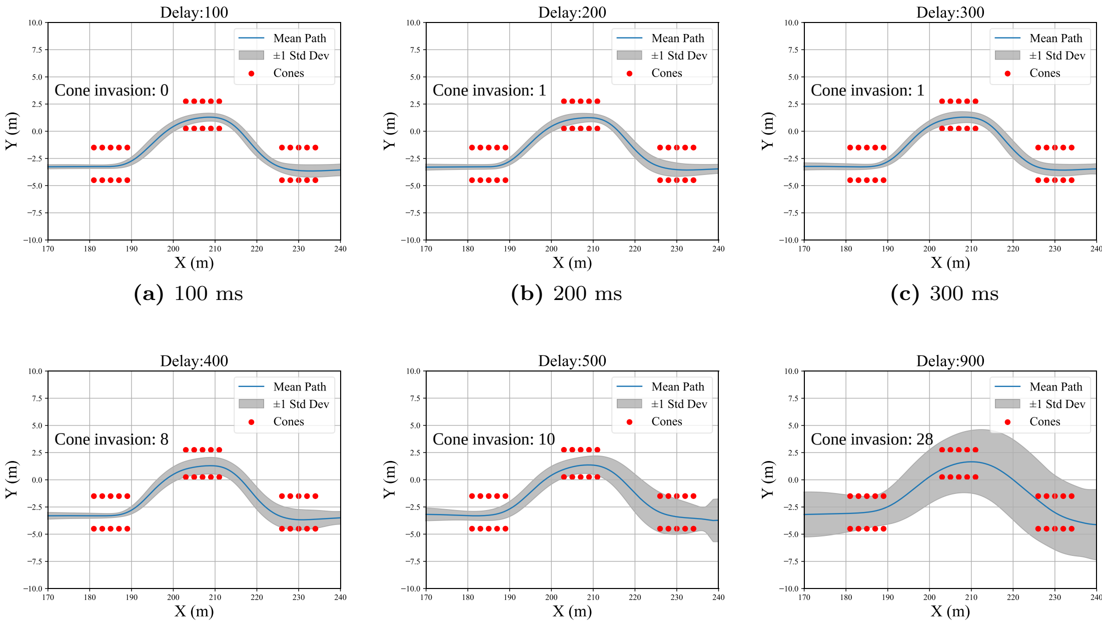

(a) 100 ms **(b)** 200 ms **(c)** 300 ms

(d) 400 ms **(e)** 500 ms **(f)** 600 ms

Fig 19. Analysis of gait driving data according to delay size

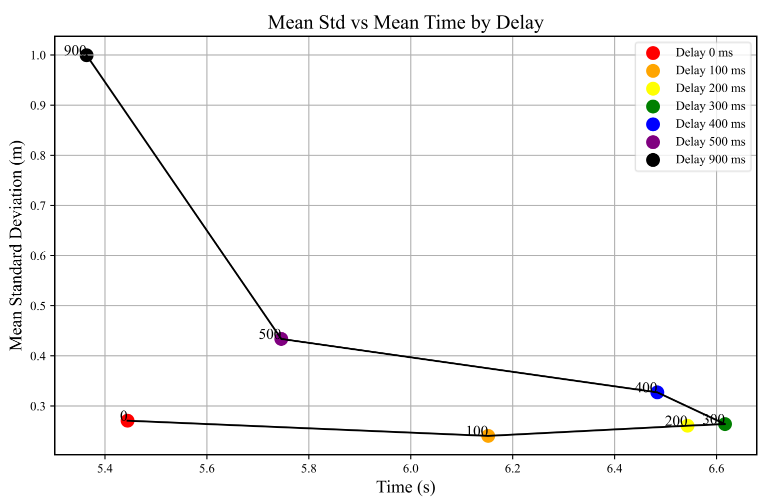

Fig 20. Variation of Time Standard Deviation by Delay Magnitude

0.19 Variation of Time Standard Deviation by Delay Magnitude

Fig.20 illustrates the relationship between the mean standard deviation of driving actions (Y-axis) and the mean time (X-axis) as a function of delay size. Each data point represents the average time and standard deviation under specific delay conditions. The

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black line connecting the mean values for each delay condition visually shows the trend of decreasing standard deviation as the delay decreases. At delay 0, driving actions show the highest consistency, indicating that when drivers receive immediate feedback without delay, steering control is highly stable, with minimal variability. At delay 900, the graph shows the highest standard deviation, indicating a lack of consistency in steering control. Furthermore, the shorter driving time in high-delay conditions suggests vehicle control is almost impossible. Notably, from delay 400 onwards, variability increases, and the driving time decreases, reflecting a decline in vehicle performance and increasing difficulty in maintaining control.

Conclusion

Teleoperation on real roads holds significant importance, requiring consideration of factors such as climate variations, traffic conditions, and unexpected obstacles, all while adhering to regulations outlined in the Road Traffic Act. Despite efforts to minimize communication delays through physical means, current compensation techniques and aids remain insufficiently robust to ensure complete safety.

This study aimed to establish a viable limit for teleoperationable communication delays through comprehensive experimentation. Findings revealed that performance degradation, particularly in terms of distance error from the reference track line, occurred between 300-400 ms (Table 6, Fig. 18) of delay. The study's contribution lies in providing acceptable benchmarks for communication delays, serving as a valuable reference for future research endeavors.

It's worth noting that the experiment relied on a driving simulator, which may pose a potential limitation. Future research could explore different maneuvering tasks and incorporate varied communication delay scenarios to create a more realistic testing environment.

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