Exploring Shared Control in Automated Driving

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***Abstract* - Automated driving systems that share control with human drivers by using haptic feedback through the steering wheel have been shown to have advantages over fully automated systems and manual driving. Here, we describe an experiment to elicit tacit expectations of behavior from such a system. A gaming steering wheel electronically coupled to the steering wheel in a full-car driving simulator allows two participants to share control of the vehicle. One participant was asked to use the gaming wheel to act as the automated driving agent while another participant acted as the car driver. The course provided different information and visuals to the driving agent and the driver to simulate possible automation failures and conflict situations between automation and the driver. The driving agent was also given prompts that specified a communicative goal at various points along the course. Both participants were interviewed before and after the drive, and vehicle data and drive video were collected.**

Our results suggest that drivers were able to interpret simple trajectory intentions, such as a lane change, conveyed by the driving agent. However, the driving agent was not able to effectively communicate more nuanced, higher level ideas such as availability, primarily due to the steering wheel being the control mechanism. Torque on the steering wheel without warning was seen most often as a failure of automation. Gentle and steady steering movements were viewed more favorably.

Keywords – Automated Driving, collaborative control, shared control, haptics

I. Introduction

Road vehicle automation implementations range from completely autonomous systems that require no driver involvement to systems that merely support a driver. In a partially automated vehicle, the driver and the computer are part of a human-robot team whose members need to share goals[1] and mental models, know their roles and fulfill them, and trust each other appropriately [2][3]. Currently, the driver's role is that of the primary controller, supported by automation both for comfort (e.g. cruise control and lane keeping) and for safety (e.g. electronic stability control).

As automated systems becomes capable of driving in more circumstances, the roles will change, with the robotic system and human driver collaboratively controlling the vehicle to a greater degree than possible today. Future automated driving systems that share control with human drivers provide an opportunity to improve safety and reduce driving fatigue compared to unassisted driving, as well as have an advantage over fully automated systems in terms of driver engagement.

Such a collaborative control [4] system allows for both the driver and the automated system to be interactively exerting control simultaneously. Haptic shared control [5], [6], where the

Fig. 1. Driving Simulator (top) and Wizard Station (bottom)

automated system applies a torque on the steering wheel to influence the driver is a promising implementation. Such a system allows the driver to feel the input from the automated system while allowing them to override or correct this input if the torque applied is small enough.

In this study, a shared-control human-in-the-loop system is used to explore how haptic torque feedback on the steering wheel can convey intent. Nineteen pairs of participants used electronically coupled steering wheels to drive through a fixed course in a driving simulator, with one acting as the driver and the other as the automated driving agent. By observing both successful and unsuccessful interactions between human drivers interacting solely through these coupled steering wheels, we can characterize gestures that could be used by an automated vehicle when sharing control with a human driver and can estimate how these gestures and gestural features are interpreted by the driver. By sourcing possible gestures from the population of participants, we are able to explore a far richer pool of possible gestures or actions than if we coded them ourselves.

II. Background

Haptic shared control is an approach to vehicle automation that involves the human-robot team of the driver and the automated system collaborating over torques applied on the steering wheel. We use techniques borrowed from the human-robot interaction literature to explore this automotive system.

A. Vehicle Automation and Shared Control

Vehicle automation has the potential to improve driving safety and efficiency and reduce driver fatigue. The common view of automated driving is a vehicle that is a hands-off feet-off system where the driver is completely disengaged from the controls and from monitoring the situation. Such systems that are capable of handling all potential road situations better than a human driver and are able to take responsibility for the safety of the occupants and the surroundings are classified in NHTSA taxonomy as Level 4 [7], and by the SAE J3016 Standard as Level IV or V [8]. However, until such systems are available, the driver will need to be in the loop, ready and capable of safely taking over control at all times.

A shared control system, where an automated system and a driver concurrently control the vehicle, might accomplish this requirement. It might also combat the cognitive underloading caused by automated systems that can induce drowsiness[9] and present a hazard when the driver has to take over control [10].

Shared control has primarily been implemented in two ways [11]: Input-mixing shared control, where the vehicle is controlled based on some combination of the automated controller input and driver input; and haptic shared control (Steele and Gillespie) [5], where the automation applies forces to the control mechanisms (usually the steering wheel) in order to influence the driver's inputs, or a combination of the two (Switkes) [6].

Shared control might also help during transitions between manual driving and higher levels of automation. For example, Abbink, Mulder and Boer [12] argue that changing the "level of haptic authority" - the stiffness of the haptic shared control force - is similar to changing the level of automation and that such a system meets the criteria for an adaptive/adaptable automated system [13]. Haptic feedback on the steering wheel has been found to be effective in inducing faster obstacle evasion[14], and in enhancing motor learning on a steering task [15].

This idea of Shared Control also has precedent in the HRI world, particularly around teleoperated vehicles. Fong [4] suggests that the human operator of a teleoperated vehicle should be modeled as a collaborator rather than a controller – considering that few drivers have extensive training, and at times may be impaired by distraction, fatigue, or substances, the vehicle can act as a supervisor, overseeing the driver's actions. This collaboration can also work in the opposite direction, with the driver supervising the automated driving. Certainly in the early period of automated driving (NHTSA level 2) it will be necessary (and is required under current law) for the driver to be continuously available to drive, if not actively in control.

B. Challenges in Shared Control

Haptic shared control of driving poses a set of challenges:

Adaptation to force: The guidance hypothesis [16] suggests that drivers (and operators of haptic shared control interfaces) show a neurobiological adaptation to the supporting force. However, they perform worse when the supporting force is removed, compared to before they experience the system. This could present a hazard when the system becomes unavailable.

Appropriate trust: Over-reliance on automation and driver complacency are issues that can affect partially automated systems such as haptic shared control. [16] It is important that the driver have an appropriate level of trust in the system [3] – being aware that the system is capable of better sensing and faster response than humans, but also capable of making mistakes. The driver should know what situations the automation is designed to handle. A driver who is 'in the loop' will be better able to react appropriately to situations presented by the environment or to changes in the system state.

Intuiting driver plan: Vehicle inputs from the driver and from automation can differ locally but combine without conflict when both the driver and the automation are on similar trajectories. Handling the differences between the inputs becomes a lot more challenging when the vehicle and the driver choose different strategies or trajectories to deal with the same road situation. For example, if in response to a car that suddenly slows down in front, the vehicle automation intends to slow down and swerve right but the driver wants to accelerate and swerve left, the two strategies that would be safe individually can combine catastrophically. So, it becomes necessary for the car to understand what the driver's plan might be based on her or his actions, and to act appropriately.

Communicating vehicle state: Keeping the driver aware of the state of the system is likely to be helpful in such situations – knowing what the system sees and how it plans to act can avoid confusion and potential conflicts between automation and the driver. Such a system might alert the driver to dangers they might have missed, and the driver might be able to catch errors in the automated system's understanding of the environment. This is a lot of information to be communicated in a short duration of time, and it is a challenge to intuitively inform the driver of this without being overwhelming.

Understanding driver responses in critical situations: It is important to look at how drivers respond to failures in automation – both false positives when the system reacts to a non-existent threat, and false negatives when the system fails to respond safely. Do drivers need special training on handling transfers of control without panicking? This is related to monitoring driver state - The driver's ability to take over control of the vehicle is dependent on the driver's engagement, how drowsy or impaired they are, and on their awareness of the situation. [9] Any changes in the level of automation will require the car to be aware of the driver's state.

Adaptive/adaptable shared control: Vehicles will have to switch the level of automation if they are to provide the convenience of automation where it is possible while giving back control to the driver when required. If this level of authority is communicated by the amount of haptic feedback, are changes initiated by the automated system or by the driver? How is this communicated to the driver? How does this transfer of control take place?

C. Communication through haptics

In this paper, we are investigating a new and unexplored aspect of haptic shared control - the implicit communication that can occur through feedback torque on the steering wheel.

The psychology governing human-robot interaction, such as the effect of communication style and dominant/subordinate behavior [17] will be significant concerns for the design of highly capable vehicle automation. Designing mechanisms and interaction schemas for collaboration [18] and coordination [19] between human drivers and automated systems will be of high importance, given the difficulties resulting from the nature of the relationship where one entity is human and one is not.

This study explores using a steering wheel in a haptic shared control system to communicate higher level messages such as the intentions or availability of the driving agent. Maclean and Roderick's haptic doorknob Aladdin [20] explores haptic feedback as a socially communicative medium. They experimented with the expressiveness and interpretation of haptic movement as the "beginnings of a linguistic framework" based on kinesthetic and tactile responses. The affective responses to rendered friction, inertia and detents in a knob has also been studied. [21]

Reed and Peshkin [22] report that humans cooperating on a haptic task show specialization of roles not observed in a human-robot version of the task. Two humans collaborating on a task of moving a 1 DoF handle to a target performed better than each member working alone. However, replacing one member with a motor that played back their force profile produced similar performance to working alone when they believed another human was applying the forces, and worse performance when they knew it was a robot. The authors suggest that this kind of haptic interaction between humans holds a "subconscious subtlety" that might also involve social behavior.

Human-robot interaction literature presented insights into a research methodology to investigate this kind of subtlety in haptic interaction on a steering wheel.

D. HRI and Socially sourcing Interaction

In this study, we source gestural interactions from the actions of human drivers communicating over a steering wheel. This technique is borrowed from Embodied Design Improvisation [23], a design method outlined by Sirkin and Ju for designing human-robot interaction. It uses staged improvised interactions between people and devices to reveal likely behaviors and responses to robot actions as well as aid in eliciting the unspoken expectations and models people have for the interaction.

A similar methodology has been used in the automotive space by Schieben et. al. [24] to design and test automated system behavior and interaction - the theater-system technique. Participants used a pair of mechanically coupled steering wheels and pedals to drive a simulated vehicle. They then act out scenarios, and the ensuing dialog about the design of the haptic interaction revealed user preferences and expectations

Humans apply a social model to interact with and predict the behavior of many technologies they interact with, including cars. Studying human behavior is often useful in informing the behavior of social robots interacting with humans [25]. The methods outlined above are a form of "Learning by Demonstration" - Knox, Spaulding and Breazeal [26] conjecture that social behavior for a robot can be learned from a "teacher" demonstrating robot actions in a Wizard-of-Oz setup.

This study also follows the contours of Research through Design, where researchers "develop and deploy novel artifacts … to learn about specific aspects of the human experience" [27]. This allows researchers to investigate how people behave or interact in new scenarios, and abductive reasoning can be used to form a conjecture based on the observations. Such a methodology is useful in an exploratory study like this one, as it allows flexibility in changing the study design to better investigate the subject based on what we have already learned.

III. System

A. Driving Simulator

The study was conducted at the Stanford Driving Simulator, a high fidelity fixed-base simulator with a full vehicle buck and a 270° cylindrical screen, LCD side mirrors, and a projected image for the rear view mirror. The steering position is read by an encoder, and torque feedback is applied using a control loading steering motor.

B. Driving Agent Station

The driving agent sits in a room adjacent to the simulator, with a Logitech G27 force feedback gaming steering wheel on a table and throttle and brake pedals fixed on the floor in front of them. A 60 in. plasma screen displays the simulated view, and stereo speakers play road and car noise. An instrument cluster on the driving agent station shows a speedometer, tachometer, and also information on the driver: the steering wheel position, whether the steering wheel is being touched, and whether the gas and brake pedals are being pressed.

C. Shared Control System

The two steering wheels are linked electronically via a teleoperation-like control loop. It is ultimately the position of the car steering wheel that decides the simulated road wheel angle, but the driving agent steering is able to apply torque to control the car steering wheel position. This allows the driving agent and the driver to feel each other's input on their respective steering wheels, and for the agent to control the car when the driver does not resist the applied steering torque. For longitudinal control, the system is currently set up so that the control with a higher input dominates. The brake or throttle moved through a higher angle will have its input go through to the simulated vehicle.

IV. Methods

Fifteen driver – driving agent pairs drove a fixed course in a driving simulator system. All pairs got the same instructions. The driver was in the full buck car, and the driving agent in a smaller simulator nearby. The driver was not told about the driving agent, and was not informed that the automated system was another human driver. As the study progressed, we modified the protocol and the system to better explore the problem of shared control based on our findings. This is tabulated at the end of this section.

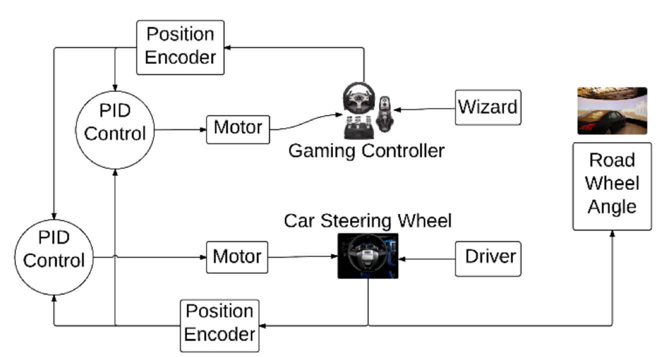

Fig. 1. Control Loop

A. Participants and Procedure

Two experimenters are involved in conducting the study – one monitors the video inside the simulator and plays pre-recorded audio prompts to the driver at predetermined locations throughout the simulated drive and another gives instructions to the driving agent. The first participant to arrive at the location is assigned to be the driving agent, and the second is assigned to be the driver. In four cases where the second participant did not turn up, we had one experimenter play the role of the driver. Nineteen sessions of the study were run. Participants were adults between the ages of 18 and 65 who had a driving permit and experience driving on the right hand side of the road.

The driving agent is brought into the simulator first, to be briefed about the system and their role as the automation. There is a 5 min practice section for the driving agent to adjust to the system. The driver does not experience this section so the do not see the learning period where the driving agent might make mistakes, and are not predisposed to distrust the automation. The driver is told that the car has an automated system that shares control of the car with them. They are not informed that the automated system is a human driver.

B. Driving Course and Events

The study is conducted on a 25 mile driving simulator course with three sections with four lane divided highways (speed limit = 65mph), four lane undivided highways (speed limit = 35 mph) and a short section of two lane roads (speed limit = 25 mph).

The scenarios tested in this study are based on likely failure scenarios of automation at Level II and Level III: A False Positive event (a situation where the automated system falsely determines that there is a situation requiring a corrective action) was created by triggering a vehicle cutting into the lane in front of the car. This cutoff vehicle is only displayed at the driving agent station, so any response to the event by the driving agent would be perceived as a mistake by the driver. A False Negative event (a situation where the automated system fails to see a threat on the road, and the driver is forced to respond to it) is created by reversing this scenario – the driver sees the vehicle cutting in, but the driving agent does not. A Level II automated vehicle might require the driver to handle sudden conflict situations like this one. In addition, there is an unexpected pedestrian incursion into the road that was visible to both participants (a True Positive).

Table 1: Event Types

Event	Perception	
	Driving Agent	***Driver***
Car Cutoff (False Positive)	Perceived	Did not Perceive
Car Cutoff (False Negative)	Did not Perceive	Perceived
Pedestrian (True Positive)	Perceived	Perceived
Normal Driving (True Negative)	Did not Perceive	Did not Perceive

At certain locations in the course, the driving agent is prompted to communicate to the driver using the controls – offering to share control of driving, prompting the driver to take back full control of the vehicle, and navigation instructions including turning at intersections and taking the exit on the highway. This allows the study to contain periods where the driving agent was in full control and the driver is disengaged from the controls, and periods where the driver is merely supported in emergencies by the agent.

Situations where the automation and the driver may be at cross-purposes are especially interesting. In the ideal case, the outcome would depend on who has the better information. It is important that automation know what the context is, and communicate the reasoning behind its actions in such a situation. A simple investigation of this problem is conducted by providing the driver and the driving agent competing information, and studying the interaction and the negotiation that ensues. As the car approaches an intersection, we instruct the driver to turn right to get to their destination. At the same time, the driving agent is informed that there is bad traffic to the right, and that a left turn would be a better option. The agent is instructed to "suggest" a left turn, and to not continue fighting the driver if they seem to not be following the suggestion.

C. Data Collection

Both participants (i.e. driver and driving agent) are interviewed before the drive about their driving habits, what they consider to be good driving, and whether they tend to be critical of the driver as a passenger. After the drive, they were interviewed separately about their impressions of the

Fig. 2. Car Cutoff Event (False Negative

experience, and what they thought went well or went poorly. The interviews were conducted free form with emphasis on trying to get the participant to lead the discussion and bring up what they found to be interesting. After the separate interviews were completed, a joint one was conducted where sections of the captured video were replayed, where the experimenter could point out an action and inquire about the reasoning behind it.

Additionally, the driver and the driving agent are monitored using HD video cameras, and the simulated road view is recorded. Drive data including vehicle position on the road, velocity and acceleration, and inputs from the driver and the driving agent were collected at 60Hz. The timing of events on the course was also marked in the data. This data was used to confirm findings from the video and the interview.

D. Iterative Design

The goal of the study to develop an understanding of the haptic language people use and to borrow effective gestural techniques that the driving agent can utilize. This is an iterative study meant to be generative and to use principles of Research by Design to modify the research artifact (the shared control system) to explore the ideas generated in this process. As the study progressed, we adapted our method to reflect what we had learned. This resulted in our having three clear phases:

Phase 1: The first seven pairs of participants were told to communicate only using the controls (steering, brake, throttle, turn signals). When we found that these controls were insufficient for communicating what we asked the driving agent to, we modified the system. These findings will be explained in more detail in the results section.

Phase 2: We ran the next 6 sessions with one of a few different systems (speech-text-speech app to disguise the driving agent's human voice, walkie-talkies for both the driver and the agent) and some different instructions (e.g. talk to each other to decide what to do on the steering in order to communicate, try and settle on a code for communication over the steering wheel).

Phase 3: The last 7 sessions were run with the driving agent always listening to the driver through a headset, and talking to driver using the walkie-talkie. The driving agent was asked to use the controls to communicate, with verbal communication over the walkie-talkie as a backup if that failed.

Table 2: Study Phases

Controls Only	***Controls + Other***	***Controls + Audio on***
First 7 pairs	Next 6 pairs	Last 7 pairs
Steering wheel, brakes, throttle and turn signals only	Exploring alternative interactions Controls + text to speech or walkie-talkie	Control + driving agent always listening to driver + Walkie-talkie for driving agent to talk to driver

V. Results

This study was intended to generate hypotheses for future test. From examining the interview and the video data, we captured some interesting interactions and have identified areas that deserve further investigation with a controlled study.

A. Communication

The study sessions suggest that moving the steering wheel let the driver perceive automation intentions like a lane change or speed change, but was not effective in letting the driving agent communicate more nuanced ideas such as intent to transfer control. This could be because the steering wheel is also the control mechanism, and any communicative action on the steering wheel (for instance, jiggling of the wheel, which many driving agents chose to do) would also be reflected in the car's motion. Forceful suggestions from the driving agent were usually not approved of by the drivers. One driver mentioned that "*the only thing I didn't like was ... when it was controlling for me when I didn't want it doing something*".

We find that the driving agents were mostly ineffective in communicating their desire to share control of the vehicle, and their input on the steering wheel was often interpreted as a failure of automation. Using the steering for purely communicative purposes was not interpreted well. The action, although miniscule in effect, affected the car's movement while it was at speed, which could potentially lead to loss of steering control and endanger the driver. This disapproval might not extend to vibration on the steering wheel though, as that would not affect the ability to control the car.

A few of the participants did not register any communication from the driving agent. *"I did find…making turns and stuff was hard, but I think that was just the simulator…No, I didn't notice an automated system, to be honest." "I felt like I was in control the whole time."* Even when the driving agent wiggled the steering wheel, one participant merely *"thought that I had lost control a little bit, and I needed to be stronger on it."*

The majority of drivers did feel the automated system, but some did not appreciate the driving agent's input on the steering wheel without warning. For instance, one driver reported that, *"[Automation] was not useful - sometimes it turned the wheel to the left well before I was told to turn left. I wasn't sure. Well, I kept thinking that maybe it was a mistake or it was faulty. I thought it would have helped if it actually … spoke a bit."*

A visual indication to the driver, even in the form of the turn signal LEDs, seem to help the driving agent communicate better. Most pairs who were restricted to the controls for communication converged on the use of the turn signals by the end of the study. This suggests that there is a strong need for another sensory channel of communication from the car to the driver, beyond haptic signals.

After we realized that the proffered signaling tools were not sufficient for effective communication, we allowed the driving agent to fall back on verbal communication – the driving agent was instructed to use the controls to communicate and, if that failed, to talk to the driver over the walkie-talkie. However, even in such situations, the driver's reactions were often non-verbal, even when given the option to talk - frowns, shaking of the head, and surprised expressions were common. These are natural and spontaneous reactions, not purposeful responses. Even in the cases where the automation (driving agent) talked more/tried to explain its actions, the driver tended to speak less than the driving agent did.

The lack of driver response showed us that many of the drivers did not consider that they could or should relay information, even simple confirmation, to the driving agent control system. This assumption, that robots or autonomous systems are not currently capable of receiving vocal information, was widespread. "*The next generation of semi-autonomous cars would be like…if it slows down and I have no idea why, I could ask it…maybe it could talk to me." "[A good autonomous car would be] reactive, like a person."* This matches findings from a study [28] that suggests that the car needs to be introduced as a social object capable of verbal communication before the driver starts talking to it.

In two of the experiments, we instructed the driver to say "Hi" to the car at the start, and had the driving agent respond to the greeting. We found that the driver and automation both verbally communicated much more in these cases. This is likely to have framed the driving agent as intelligent and capable of receiving and interpreting information from the driver.

B. Communicating availability

When asked to communicate to the driver that they were available for sharing control, many driving agents tended to try and jiggle the steering wheel so the driver would feel the torque.

This action was counterproductive though, since in most cases this alerted the driver to an external influence on the steering, but did not inspire confidence in the automation.

Some driving agents chose to force a lane change maneuver when the driver had not done so, and this action seemed to be largely successful. The driver noted that automation was influencing their trajectory, and that the action seemed safe, even though it was unprompted. The drivers' compliance seemed to be based on their belief that the automation was capable of making such decisions, and on the lack of an obvious danger. The act of using the turn signals before the lane change also alerted the driver to the driving agent 's intentions. Most driving agents were diligent about turn signal use. The lane change was effective in building trust in automation, since this usually took place while on the highway, where the traffic was sufficiently low, and thus was a low-risk situation.

Driving agents were often unsure if the message had been received, because a cooperative driver wouldn't fight their input, and as long as the driver left their hands on the steering wheel (showing no change in the "steering wheel touched" display), the agent had no feedback that the driver was relying on them.

Communication through the controls was sufficient for the driver to pick up on driving agent intention, but not for inferring confidence, intent to take over, and intent to give back control, which became more critical in the false positive and the false negative situations. When verbal communication was allowed as a backup, driving agents mostly echoed our instructions to them – for instance, "I am ready to share control" when we told them "You are now ready to share control of the car with the driver. Please find a way to communicate this to the driver using the movement of the steering wheel. If you find that it does not work, please talk to the driver using the tablet/walkie-talkie."

C. *Communicating unavailability*

Driving agents found it challenging to use the steering wheel to let drivers know that they would need to take full control – when the drivers trusted the system, wiggling the steering wheel did not seem to convey this successfully. In most cases, the driving agent flashed the turn signals instead, mimicking the hazard emergency lights.. Other driving agents opted to release the throttle and let the car coast until the driver noticed.

D. *Event: False Positive*

The false positive event was mostly met with surprised looks, but very few drivers really took over or hit the throttle to compensate or verbally commented about it during or after the study. This action may not have been sufficiently interesting, however, as the driving agent's appropriate action to avoid the cutoff car was to merely brake while staying in the same lane. Perhaps an apparently unnecessary and possibly risky swerve would elicit a stronger reaction from the driver. One of the participants seemed to combine this event with other un-communicated driving agent behaviors and came to the conclusion that the driving system was unreliable. "[I took control more often on the highway, because that] was when it was going back and forth a lot."

E. *Event: False negative*

The false negative event is more difficult to analyze. Most participants did not consider whether the automation was involved in helping them during the critical moment, and do not remember clearly during the post-drive interview. Drivers do perform worse on the false negative car cutoff than drivers in other studies with a similar event while in manual driving. This could be due to the complacency of shared driving, or due to the driver being out of the loop.

F. *Event: Conflict Situation*

In the conflict situation, drivers most often followed the audio prompt from the experimenter, turning right. The driving agent tries to convey a suggestion to turn left because of bad traffic to the right, most often using the turn signal or trying to move into the turn lane in advance, but most drivers choose to do what they had been verbally instructed to do, going against the suggestion from the driving agent.

However, in a couple of the cases with high trust in automation, the driver ended up being conflicted and compromised by going straight, instead of to either side. When audio communication was allowed, participants followed the driving agent when it was safe to do so, probably because it came after the experimenter's audio prompt and was clear in its intent, demonstrating authority and making the driver more inclined to trust the driving agent.

G. *Using prior experience as a template*

When given the freedom to talk, a couple of the driver-driving agent pairs negotiated very limited features based on existing systems they had used – a few drivers ceded only throttle/brake control while maintaining control of the steering. Another driving agent was asked to act as a cruise control (not adaptive cruise control) system, and did not respond to the car cutoff and drove into the vehicle, because he felt that that did not fall within the responsibilities of a cruise control system.

H. *Gender effect*

Five of the pairs that participated in our study were female-female, and they seemed on average to have slightly more communicative and successful drives. Drivers in these pairs seemed to have higher levels of trust in automation, seemed to more easily correctly interpret signals through the steering wheel as communication, instead of malfunction, and also remain more engaged during the entire drive. The females also seemed to show more consideration for the other participant, and helped them by trying to communicate, often politely. This matches prior literature that suggests that females might be more empathetic than males. [29] [30]

Male participant drivers remarked frequently that they had been disengaged during at least part of the drive. The drive "was long, and kind of boring." The female drivers more often remained engaged throughout the drive, even when they were in a passive mode and the other participant was handling the driving. Even when not fully controlling the car, the females expressed that they were responsible for the car's actions. One of the women was reluctant to even use the walkie-talkie because she didn't want to be a distracted driver, even with the engaged automated system.

The communication between the pairs was calm and even polite. When one of the driving agents was instructed to take control, she said, "I can take over now." In another pair, the driving agent apologized to the driver in the false positive situation. “I’m sorry for braking harshly, but there was a jerk on the road.” Overall, female drivers demonstrated conscientiousness toward the driving system and treated it as more human. Female-female pairs were the only drivers to let the driving agent influence them in the conflict situation.

I. Complacency/Mode error

Many participants let go of the steering wheel and sit back when automation is active, even though they were only told that the system "shares" control. This matches prior literature [31] that suggests that people might not have clear models of responsibility. Some drivers let us know that they assumed the car was responsible for their safety when they were sharing control. We find that many of the drivers who considered themselves responsible (when asked about it in the post-drive interview) still did let go of the steering wheel when automation proved reliable. However, most drivers react to the false negative event when the car fails to do so.

We did not observe many indications of sleepiness, and there was no prolonged eye closure (eyes closed for more than five seconds) observed.

J. Negotiating driving styles

When there were obvious differences between the driving agent and the driver in the driving style, usually in preferences of lane or adherence to the speed limit, they seem to adjust to each other after fighting a bit, for less than 10seconds in most cases. This was most clear in the speed they chose to maintain. The more cautious driver would hit the brakes, and sometimes this would result in a tug of war on the brakes/throttle. The brake/throttle control is implemented here so that the higher input between the driver and the driving agent will override, so if one is on the brakes and the other is on the throttle, we have an engine fighting the brakes.

In some of the sessions where verbal communication was an option, the driving agent chose to speak about this, but it was usually phrased as “the speed limit is x” rather than “you’re going too fast”. The drivers tended to follow the driving agent when they initiated lane changes, but some driving agents had a bit more trouble getting drivers to go along with their suggestions on turns and exiting the highway, particularly in the cases where the drivers had decided that some of the torque on the steering wheel was due to a malfunctioning system.

VI. Discussion

The study has identified areas of interest and potential avenues for research on shared control of the vehicle. The primary finding of the study is that the steering wheel motion was not sufficient to communicate intent and future actions to drivers. The driving agents were unable to come up with an intuitive and compelling haptic gesture. This could be because the haptic coupling did not provide enough bandwidth for such communication, or perhaps because of the steering wheel being the control mechanism that the driver expects to correspond to vehicle movement. This study also demonstrates an iterative and generative research methodology that can investigate human behavior in relation to robots.

A. Implications for design

The haptic behavior on steering wheel does determine the driver’s opinion of the automated system, but participants who act the role of automation are not effective at communicating more nuanced information like a desire for transfer of control. Forces on the steering wheel were often interpreted as failures of automation rather than as communication – it seems important that the actions of automation be preceded or explained by other interface modalities.

A gentler driving style from the driving agent was almost universally more accepted by the driver. Haptic shared control systems need to choose trajectories that not only optimize the movement of the car, but also the movement of the control mechanism(the steering wheel). This becomes challenging in the context of shared control as emergency support, when the system may conflict with the driver and communicate that conflict through the haptic steering controls. This may mean that simply increasing the haptic force to increase “haptic authority” is not be an effective way of implementing adaptive automation with a naïve driver.

Designing systems such that drivers trust the system enough to use them properly, but not to engage in abuse [32] will be a significant concern, especially given the possibilities of false positives and false negatives. Effective communication between the automated system and the driver is essential for proper trust.

Our findings about the need for another communication channel point us towards other modalities for high-level communication – visual, auditory or forms of haptic feedback. Participant comments in interviews suggest that they believe verbal communication would work best in the situations they faced in our study.

B. Reflection on method

The research methodology we adopted gave us the flexibility to look at many possibilities when it became clear that the steering wheel was not sufficient for the communication required. We added other channels including visual feedback for the driving agent and verbal communication with driver.

The framing of the experience really affects how the participant responds – we know from other studies in the lab that when participants are told that they are training an automated car, they act differently from when they are told they are driving the car. This was why we needed to make sure that changes to the script between participants needed to be limited, and noted methodically to ensure that they were not the primary cause of differences between sessions..

Participants are rarely able to remember the entire course clearly - events often get mixed together in their recollection. To inquire about specific events, we followed seperated interviews with a second interview with the driver and the driving agent together in front of the recorded video where we point out interesting actions and try to get an explanation of their intent or reasoning.

To avoid the influence of participant familiarity, we had individual study signups, and separated interviews so it was not obvious to them that they would be participating in the same experiment. This worked well when the driving agent was restricted to using the controls for communication. When the driving agent was allowed to talk to the driver over a walkie-talkie, this charade was less effective. Accents/knowledge of English affected the quality of interaction between the participants when verbal communication was allowed.

Small variations in how the system was introduced can produce big changes in the attitudes and response to the drive, so it was important to have a script and stick to it; however, the study also required flexibility in design. As explained earlier in this document, we found a balance by using the same system for the first seven participants, then trying out variations in the next six before settling on a new version for the last seven.

VII. Future Work

The study results point to a few avenues for research. Inferring driver intent through steering wheel gestures is promising. Controlled studies comparing haptic shared control False Negative and False positive events with on-off automation have not been conducted yet. We are investigating the possibility of modifying the behavior of automation based on the driver's corrections – what can we learn from when and how the driver chooses to intervene? Decoupling the feedback from the control mechanism by using vibrations or skin stretch might allow for more nuanced communication over the steering wheel. Haptic shared control looks to be a likely implementation in the partially autonomous vehicles of the next decade, and compels further investigation.

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