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Take the Wheel: Effects of Available Modalities on Driver Intervention

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Abstract— **While automated driving systems will become increasingly capable and common in the future, there will still be instances when human drivers want or need to make corrections to the car's automated driving behavior. We conducted two studies exploring how driving interfaces could be designed to better execute the drivers' intentions. In our first study, adult participants (N=40) experienced a simulated driving scenario that varied the behavior of the car's automation (*perfect driving* and *imperfect driving*) and the intervention modalities (*takeover* and *takeover+influence*). At certain segments, the car's automation would drive perfectly or weave within the lane. During those times, participants could intervene using the available modalities. When experiencing instances of imperfect driving, drivers who had the ability to *takeover+influence* intervened more often than drivers who were only given the option to *takeover*. As intervening would require them to resume full control, drivers in the *takeover* condition were more tolerant of the imperfect driving. Also, most drivers tried to intervene initially by influencing the car, even those drivers who were only given the ability to takeover. In our second study, we examined how participants (N=40) of different demographics (high school students and seniors) would respond when they were subjected to the *imperfect driving* scenarios. High school drivers intervened just as much as the adult drivers. However, senior drivers intervened far less. These two studies suggest that when intervention is necessary, human drivers have a desire for shared control, which allows them to act as supervisors rather than operators of automated vehicles.**

I. Introduction

What is the right way for human drivers to retake control in partial automation scenarios? NHSTA guidelines specify that in Level 2 automation systems that drivers need to supervise the vehicle and take over control from automation. However, the manner in which that supervision and take over should occur is left largely unspecified. [1] Drivers may be required to intervene in emergencies, but they will also be permitted to intervene at their discretion. For example, the vehicle may be operating within its safety bounds, but driver feels uncomfortable about the automation's driving. If the steps needed to intervene or to transition from autonomous to manual mode are cumbersome, drivers might be more tolerant of an automated vehicle's driving imperfections. Hence, it is important to understand how different available intervention modalities (where drivers can perform different roles) can affect drivers' tendencies to intervene when the car's automated driving system does not function perfectly.

Figure 1: The Stanford Driving Simulator.

This paper describes a series of two studies that used a simulated driving environment (Fig. 1) where control of the car could be alternately shared between a human driver and the vehicle's automated driving system. For the first study, the experiment condition experienced by participants varied along two dimensions: the automation's driving behavior and the available intervention modalities. For the automation's driving behavior, the car could either perform *perfect driving*, where it always drove exactly in the middle of the lane, or perform *imperfect driving*, where the vehicle would weave within the lane. For intervention modalities, all participants were given the ability to perform a *takeover*, which required them to disable automation and take on an *operator* role. Half of the participants were given another available modality (*takeover+influence*), they were able to influence the car without disabling the automation. With this, participants were able to give the car small adjustments to help correct its driving. This gave the participants more of a supervisory role. In the second study, participants of different demographics were provided with different intervention modalities but only with imperfect automated driving. By examining the results of these two studies, we can better design transitions for control of automation and intervention modalities to improve the road safety and provide drivers with greater comfort.

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II. Background

Our research was motivated by insights found in our previous work [2], wherein we noted that drivers were quite sensitive to the driving performance of vehicle in autonomous mode. Even subtle deviations in movement from the ideal were readily noticed by participants as the drivers indicated that there were times that the car weaved, deviated from the center of the lane or cut the corner on a turn. However, no participant requested to take back control when these instances of notable poor driving occurred. It was suggested that while the movement might make the participants feel uncomfortable, the car's actions were not bad enough to make drivers feel that they should take back control over the automated vehicle. The drivers still trusted in the automated driving system, but they just wanted to give a quick "nudge" to help correct the car's driving behavior. From this, we surmise that drivers have a desire for shared control in certain autonomous driving situations.

In a shared control system, a human driver and an automated system are able to simultaneously exert control of the vehicle. A driver sharing control with an automated vehicle can be considered as a collaborator rather than a supervisor. [3] The driver can stay in the loop and influence the automated system's driving, or the automated system can monitor the driver and support their driving. At higher levels of automation, the driver may be out of the loop and suggest changes to the trajectory by their inputs on the controls. This is a very different paradigm than either/or control systems, where the driver is either actively driving or otherwise supervising the car's driving.

Although shared control systems may muddy the issue of "who is really driving"—a critical distinction for liability reasons—they may also allow benefits of automation and human control, improving safety and reducing driver fatigue while retaining human perception and decision making. Sharing control may also keep drivers from becoming sleepy and complacent due to cognitive underload, [4] when the car is performing ideally. The potential for providing input to the car's control may also increase driver situation awareness, [5] keeping the driver in the loop and ready to respond to a road event or undesirable driving.

While there have been evaluations of different shared control implementations, [6,7,8] not many studies have examined how the way that a driver is permitted to intervene or retake control affects the likelihood or frequency of that action. Some of the most common ways for a driver to intervene is to press a button to take over control of the vehicle. [9,10] However, there are other implemented modes that utilize subtler driver inputs to infer if a takeover should occur, such as the change in steering wheel angle created when a driver grabs ahold of it. [9,10] Blanco et al. conducted a recent NHTSA sponsored on-road study that provided participants with a large number of intervention modalities to disable automation--brake, throttle, steering wheel input, and off button on steering wheel. [11] This study reported that participants were able to react to imminent danger alerts in less than 1 second and were able to regain control in less than 3 seconds. However, there was no examination of which intervention modality was most frequently utilized or what participants thought was natural to do when asked to take back control. In addition, this and other similar studies [12], created situations that required the drivers to respond. In our study, we wanted to examine if different intervention modalities would make drivers more likely to respond, so we created scenarios where the need for drivers to intervene was more ambiguous.

III. Methodology

A. Simulator

The Stanford Driving Simulator (Fig. 1) is an immersive, high-definition driving simulator composed of two parts: a whole car and a visual display system. The first component is a Toyota Avalon that has been modified to provide participants with a realistic interface for the simulation. Both the steering wheel and pedals provide haptic feedback to drivers, creating a high degree of presence [13]. The other component is a 22-foot diameter, 270-degree field of view screen, which surrounds the car. A projector is used to display the rear view, and LCD panels are installed acting as side view mirrors. To monitor and record the driver's behavior, we have installed several wide angle GoPro cameras and microphones inside the simulator cabin.

The simulation course is a VRML file that is built using the Internet Scene Assembler software. To create the course, we combined various road segments, such as two-lane city streets and four-lane highways, together. Various cultural features, such as buildings and vegetation, were added along the road segments to help increase the driver's immersion. The behavior of the environment, as well as objects within the environment, were scripted with Javascript, which we could link to "sensors" placed in the course. For example, when the participant's car crossed a sensor, we could make the automation weave within the lane for a period of time. When completed, the course could then be utilized by Realtime Technologies' SimCreator software to create the simulation, providing the audio and video outputs.

B. Course

The course was composed of three distinct sections. There were segments when the participants would have to drive the car manually, and there were segments where the automated driving system would be in control. As seen in Fig. 2, the first section contained a three-minute practice with a full assortment of road types, so that the participants could become more accustomed to the simulated driving environment. After pulling out of a parking lot, participants would experience straight roads, curves, intersections, roundabouts and a transition from a two-lane road to a four-lane road. At the end of the first section, participants were asked via an audio alert to enable automated driving. Participants could still take control of the car at any time, but it was intended for the automation to perform the majority of the driving during the next 12 minutes of the second section. While mostly composed of long segments of straight road, this section also contained several curves. It then transitioned midway from small town streets into a freeway.

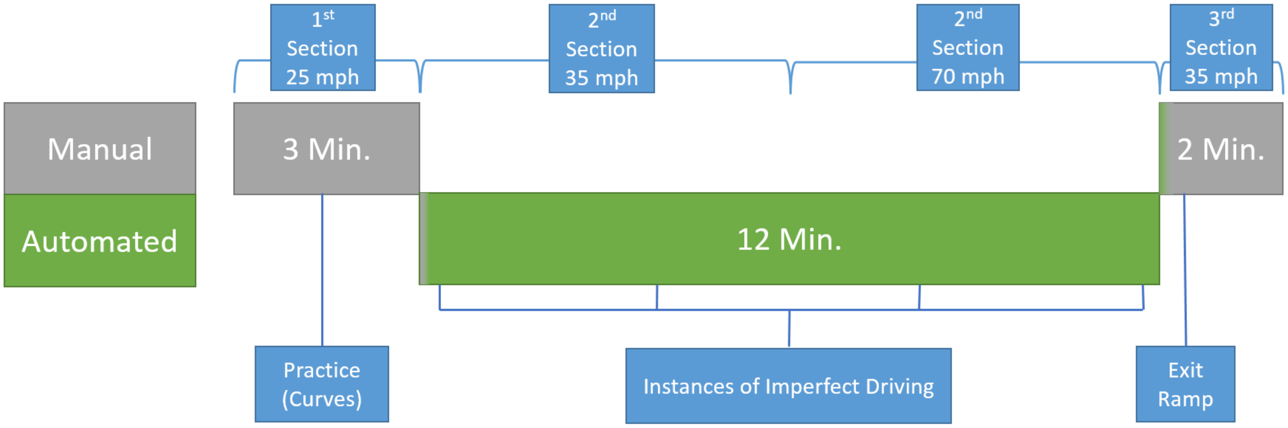

Figure 2: Course diagram outlining the three sections present in the study.

For participants in the *perfect driving* condition, the automation always performed ideally during this second section. The automation always remained in the middle of the road and also handled the curves ideally. Conversely, for the *imperfect driving* condition, participants would experience four instances of imperfect driving throughout the second section (see Fig. 2). Each of these instances occurred on a different type of road: a 35 mph undivided four-lane straight road, a 35 mph undivided four-lane curved road, a 70 mph divided four-lane straight road, and a 70 mph divided four-lane curved road. During these instances, the car would pass through a sensor that forced the automation to vary its road offset sinusoidally, causing the car to weave within the lane. Additionally, during the two curved road segments, the car would also exhibit some variation in speed from following the desired road offset. After exhibiting this behavior for 10 seconds, the automation would resume driving normally. If the driver had intervened with one of the modes provided to them, the automation would also resume driving normally once control was relinquished.

At the end of the second section, participants were asked to disable automation and take the exit ramp on the right. After regaining control, the participants experienced two more minutes of manual driving before reaching the end of the course, where they were asked to pull over and park the car.

Figure 3: Simulator's steering wheel. Buttons used for takeover and copper tape used for influence.

C. Intervention Modalities

There were two possible modes for participants to intervene when the automation was driving. The first modality was to *takeover* control by disabling automation. This was done by pressing a button on the steering wheel (see Fig. 3). A high visibility red label was placed on the button to make it clear and easy for the participants to push in the darker simulator room environment. When this button was pressed, an icon on the instrument cluster would change to indicate that automation was off (see Fig. 4). At this time, the vehicle relinquished full control of the driving to the participant in a manual mode. The participants in every condition had access to this intervention modality.

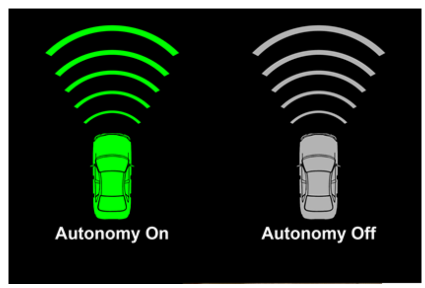

Figure 4: Indicators on instrument cluster.

The second intervention modality used an instrumented steering wheel. When participants grabbed the steering wheel, they temporarily gained full control (steering and gas/brake) of the car. During this mode, the indicator on the instrument cluster would still indicate that automation was on. When the steering wheel was let go, the automation would resume driving instantly. The steering wheel interface was implemented using a capacitive sensing copper strip under a layer of black grip (see Fig. 3). The capacitive sensor sent an analog signal to an Arduino microcontroller, which determined whether and how long the sensor had been touched. To avoid false positive signals (where an accidental touch), the car did not register an intervention until the participant had held it for at least 0.5 seconds.

D. Procedure

When the participants arrived at the driving simulation lab, they were given the study and video consent form to read and sign. Then, the participants were asked to complete the pre-drive questionnaire, which inquired about their driving tendencies and their current state of being. Once the participants finished the pre-drive questionnaire, they were led into the simulator room. To reduce variation and driver distraction, the participants were asked to silence and hand over their electronic devices during the course of the drive. Each participant was assigned one of two automation behavior conditions (*perfect driving* vs *imperfect driving*) and one of two intervention conditions (*takeover* vs *takeover+influence*). Regardless of conditions, they were given the same instructions about the vehicles autonomous driving capabilities. However, based on the modalities available, drivers in the different intervention modality conditions were given different instructions.

After getting in the car, participants were asked to properly make seating and mirror adjustments. After the recording equipment was started, the participants were briefed on the vehicle's automated driving system (the car had an automated driving feature that enabled the car to control its steering and speed). They were instructed that throughout the experiment, there were times during which they should either control the car or employ its automated system. Participants were advised that the car would provide audio and visual alerts signaling for a transition to the automated driving mode when it was required. They were advised that to enable the automated driving system, they should push a button on the steering wheel when the command from the car was delivered. Participants were also told that they would receive commands to disable automation, which they could do by pushing a different button on the steering wheel. To ensure that the participants had sufficient practice driving in the simulator, they were given time to drive manually until they heard the first audio alert asking them to enable automation, which occurred after they passed the first roundabout and intersection.

The participants were also informed that at any point in time after this first audio alert, they were free to enable or disable automation as they wished. This allowed the participants, particularly in the *imperfect driving* condition, to know that they could intervene when necessary without potentially priming them with the knowledge that they would be experiencing instances where the car would perform poorly. However, because of this freedom, there was a possibility that participants in the *imperfect driving* condition might not experience the instances of imperfect driving, if they had opted to take back control right before the segment where imperfect driving occurred. To mitigate the possibility that some participants missed the instances of *imperfect driving*, all participants were advised that they were helping to train the car that day and that they should allow the automated driving system to perform the majority of the driving task. If the participants were subjected to the *takeover+influence* condition, they were also informed that grabbing the steering wheel while automation was enabled would allow them to influence the car's driving. After additional information of the driving tasks and rules of the road were discussed, the participants were then allowed to drive. Once the participants were done with the driving component, they were asked to complete the post-drive questionnaire concerning their driving experience.

IV. Study 1: Driver Intervention

A. *Participants and Conditions*

We recruited a total of 40 participants for the first study. The majority of these adult participants were from the general Stanford University undergraduate and graduate student pool. Participants were also recruited through the university's staff networks and other popular community groups. The ages of our participant population ranged from 18 to 66 years old (M = 26.2 years, SD = 12.1 years). For this study, participants were subjected to experience one of four possible conditions (*takeover* and *perfect driving*; *takeover+influence* and *perfect driving*; *takeover* and *imperfect driving*; *takeover+influence* and *imperfect driving*). The study took an average time of 45 minutes for each participant to complete. Participants were compensated with a gift card or academic credit.

B. *Analysis*

The driver behavioral data was collected by the experimenter during the course of conducting the study. Throughout the drive, the experimenter watched the participants through a live front facing video feed and took notes of the actions that they performed in the car. Videos of the study were recorded and later reviewed to confirm the notes written by the experimenter. Reviewing the videos also allowed researchers to observe behavior that might be difficult for the experimenter to determine in real time, such as momentary displays of sleepiness by the driver.

1) *Driver Intervention*

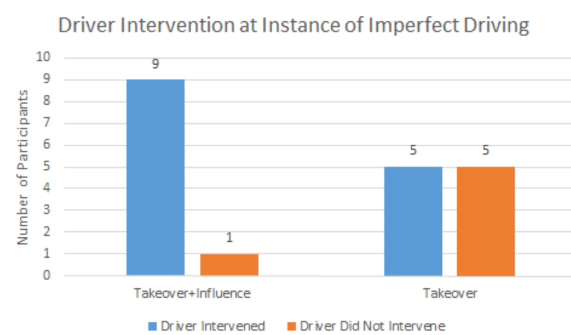

Figure 5: The number of drivers who intervened for the *takeover+influence* condition and for the *takeover* condition.

The main behavior that we wanted to measure was whether the participants intervened during any of the four instances of imperfect driving that they might experience. Since the two conditions with perfect automated driving did not contain instances when the car weaved within the lane, they subsequently did not induce any need for the participants to intervene. For this analysis, we defined a driver intervention to be any action by the participant that led to a change in the car's movement. In this case, participants needed to use one of the given intervention modalities (*takeover* or *influence*) to do so. Therefore, simply hovering a hand over the steering wheel while the automation performed imperfectly was not classified as an intervention.

A binary measure of whether any intervention (one or more) occurred showed a significant difference between conditions on the Chi Squared test (χ^2=3.81, df=1, p=0.05). Of the participants in the *takeover+influence* condition, a total of 9 participants intervened (Fig. 5). However, in the *takeover* condition, only 5 participants tried to intervene.

2) Initial Intervention Modality Utilized

Another measure was the initial intervention modality that participants used when they encountered the instance of *imperfect driving*. For this measure, only those participants who intervened were used for comparison. While the two intervention modalities that we expected to see were the *takeover* and *takeover+influence*, there might be other actions that the participants would naturally perform in an attempt to intervene, such as stepping on the brake pedal. However, from reviewing the video data, only *takeover* and *takeover+influence* were used.

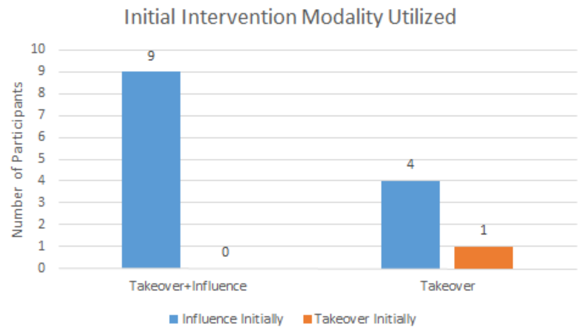

Figure 6: The initial intervention modality utilized by the drivers in the *takeover+influence* condition and for the *takeover* condition.

Performing a Chi Squared test (χ^2=1.94, df=1, p=0.16) we do not see a significant difference between the two conditions (Fig. 6). Of the participants in the "takeover+ influence" condition, a total of 9 participants intervened initially using influence. In the *takeover* condition, only 1 participant initially intervened using the *takeover*. The other 4 participants utilized influence initially, which was surprising as they did not know of the intervention modality.

3) Sleepy Behavior

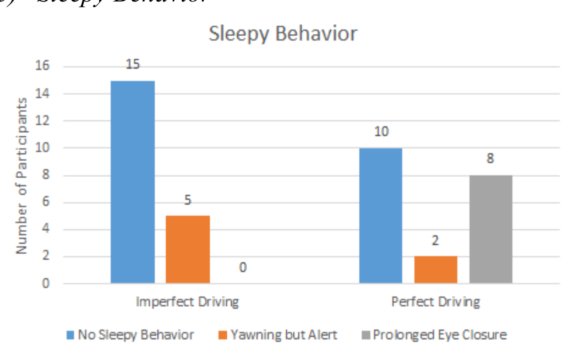

Figure 7: Sleepy behavior for the *imperfect driving* condition and the *perfect driving* condition.

Previous research indicated that drivers in autonmous vehicles might become sleepy if they did not have sufficient things to do to keep them stimulated [5]. Hence, sleepy behavior is an important factor to consider for automation. For this measure, we visually coded video recordings of the study for the participants' sleepy behavior. The behavior was further classified based on the actions of the participants. The two indicators of sleepiness that we used were yawning and prolonged eye closure (over 1 second) [14].

Performing a Chi Squared test (χ^2=10.3, df=2, p<0.01), we note a significant difference in sleepy behavior between the *perfect driving* and *imperfect driving* conditions (Fig. 7). Of the participants in the *imperfect driving* condition, only 5 participants exhibited sleepy behavior, with all 5 appeared to yawn during the study. The other 15 participants in the *imperfect driving* condition did not show any sleepy behavior. Conversely in the *perfect driving* condition, 10 participants exhibited sleepy behavior, with 8 participants displayed prolonged eye closure and 2 appeared to yawn during the study. The other 10 participants in the *perfect driving* condition did not exhibit any sleepy behavior.

4) Self-Reported Attitudinal Data

In part of the post-drive questionnaire, participants were asked which of two words better described the system. The two words were placed on opposite ends of a 7-point Lickert scale (ex. 1=safe; 7=unsafe) and participants selected an appropriate value. Performing a two-way ANOVA test, we found several significant results (see Table 1).

Table 1: Self-reported attitudinal responses of how the automated driving mode was perceived by participants. Significant results are in bold.

Question	Automation Behavior	Intervention Modality
I felt the automated driving mode in the car was (secure – insecure)	**F(1,34)=16 P<0.01**	F(1,34)=1.56 p=0.220
I felt the automated driving mode in the car was (unpredictable – predictable)	**F(1,34)=4.36 p=0.0448**	F(1,34)=0,012 p=0.913
I felt the automated driving mode in the car (unsafe – safe)	F(1,34)=2.91 p=0.0978	**F(1,34)=4.55 p=0.0408**

Participants were asked how they "felt the automated driving mode of the car was." For the questions pertaining to how secure or predictable it was, we see that participants in the *perfect driving* condition perceived the car to be significantly more secure (see Fig.8) and more predictable (see Fig.9) than those in the *imperfect driving* condition. There appears to be no significant difference between the *takeover* and the *takeover+influence* conditions.

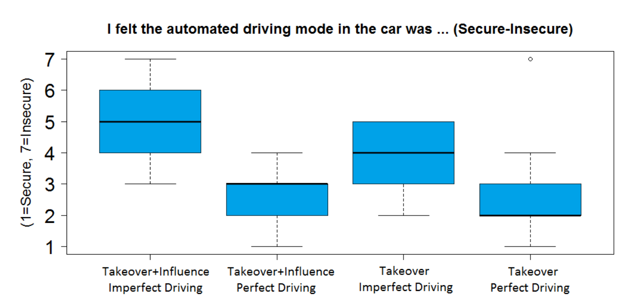

Figure 8: Responses to whether the car was (secure-insecure).

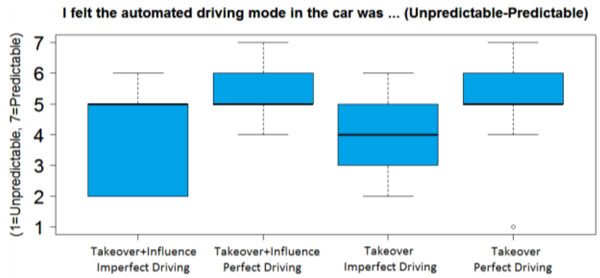

Figure 9: Responses to whether the car was (unpredictable-predictable).

With the question regarding whether the participants "felt the automated driving mode in the car was (safe-unsafe)", we do not see a significant difference between the *perfect* and *imperfect driving* conditions (see Fig. 10). Though, there appears to be significant difference between the *takeover* and the *takeover+influence* conditions, with the *takeover* condition was viewed to be significantly safer. This is likely due to the sharp corrections that occurred when participants relinquished control to the *influence* modality.

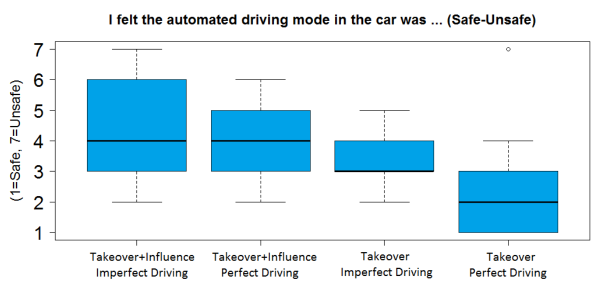

Figure 10: Responses to whether the car was (safe-unsafe).

C. Discussion

1) Implications for Design

Based on the results of the driver intervention analysis, we see that significantly greater numbers of participants intervened when the drivers were given both possible intervention modalities (*takeover+influence*) than they were given just one (*takeover*). From the observations made in our prior work Mok et al. [2], we noted that in situations where automated driving system made small mistakes, participants had a desire for a form of shared control that allowed them to make small corrections to the car's driving behavior. The drivers simply wanted to have a supervisory role and did not desire to become the operator again just because the car drove imperfectly. The results of this measure reinforced this hypothesis, as drivers in the *takeover* condition were much more tolerant of the vehicle's bad driving and they were unwilling to perform a takeover to resume full control.

In the post study interviews, many of the drivers "did not feel that the car was driving badly enough to turn off the autonomous mode." Another driver said "it was bearable because it still stayed between the lines and other cars were far enough away." For the drivers of the *takeover+influence* condition, the added intervention modality of influence did not require the driver to take full control. Drivers thought that it was simple enough to use, with one saying "it was easy enough to straighten out the car when I wanted to." So accordingly, we see that drivers in this condition were much less tolerant of *imperfect driving* and acted to correct when necessary. Although drivers did not perform significantly different actions (touching the steering wheel vs pushing a button) to utilize each intervention method, the perception of having to resume partial control vs full control was enough to alter the drivers' behavior and decision making.

The observation of the initial intervention method that drivers performed provided an insight into how intervention modalities should be designed. It is clear that grabbing the steering wheel in order to make a correction is the reflexive and natural action for drivers to perform. It is not surprising that all the nine drivers who intervened in the *takeover+ influence* condition utilized *influence* first as it was perceived to be the more favorable of the two modalities to use. However, it is interesting that four of the five drivers in the *takeover* condition also initially tried to use *influence* (grabbing the steering wheel). This intervention modality was unavailable and unknown to them. Furthermore, they were told that the only way to disable the automation was to push the button on the steering wheel. So, it is interesting that a large portion of these drivers still tried to grab steering wheel and turn it. Grabbing the steering wheel seemed to be the intuitive way for most drivers to regain some control. Therefore, it is important that cars be designed to detect when the steering wheel is touched or moved. Otherwise, the exclusion of this intervention modality can hinder drivers and lead to poor performance as they have to perform an action that is different from what is instinctive to them.

2) Observed Driver Behaviors

From the results of our studies, a greater amount of sleepy behaviors were observed during the *perfect driving* condition. However, it is important to note that the types of sleepy behaviors displayed were different. For *imperfect driving* condition, all of the drivers who displayed sleepy behaviors appeared to be yawning but still alert. With *perfect driving* condition, 8 of the 10 drivers who displayed sleepy behaviors exhibited prolonged eye closure of over 1 second. It appeared that the *imperfect driving* had caused the drivers to be more alert because of the car's questionable movement and behaviors. The vehicle's weaving would mostly likely cause the drivers to feel a greater sense of uncertainty and also a need to monitor the car to make sure it did not perform any dangerous actions.

For sleepy drivers in the *imperfect driving* condition, they had yawning, but they did not exhibit any prolonged eye closure. They seemed to be attentive and the act of yawning was likely used to keep themselves awake so that they could continue to watch the car's actions. In contrast, sleepy drivers who experienced the *perfect driving* condition often exhibited prolonged eye closure. As no kinks occurred in the drive, the drivers apparently did not have motivation to be alert and monitor the car. This might have caused drivers to "give in" to the sleepiness that they had felt during the drive. Hence, *imperfect driving* could cause the driver to view the car's driving behavior negatively, it could also keep drivers awake and vigilant—an interesting tradeoff.

V. Study 2: Demographics

A. Participants

We recruited a total of 40 participants for the second study. The high school drivers (N=20) were recruited from local high schools or through various summer programs. The ages of the participants ranged from 15 to 19 years old (M = 17 years, SD = 0.94 years). The senior drivers (N=20) above) were recruited through popular community groups. The ages of the participants ranged from 60 to 77 years old (M = 67.5 years, SD = 6.13 years). For this study, we only wanted to examine participants' responses to imperfect driving. So, participants were subjected to experience only one of two possible conditions (*takeover+influence* and *imperfect driving*; *takeover* and *imperfect driving*). The study took an average time of 45 minutes for each participant to complete. Each participant was compensated with a gift card.

B. Analysis

1) Driver Intervention

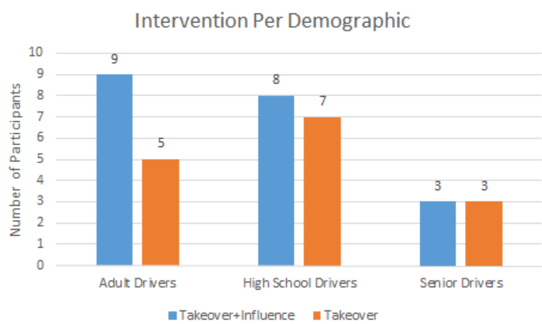

Figure 11: The intervention for each of the three demographics for *takeover+influence* condition and the *takeover* condition.

With the high school drivers (N=20) whom we tested in the *imperfect driving* condition, we do not see a significant difference in driver intervention between the *takeover* condition and the *takeover+influence* condition. Performing a Chi Squared test (χ^2=0.27, df=1, p=0.61) we do not see a significant difference between the two conditions. With the *takeover+influence*, 7 drivers intervened, while with the *takeover*, 6 drivers intervened (see Fig. 11).

With the senior participants whom we tested in the *imperfect driving* condition, we also do not see any significant difference, as the same number of drivers intervened in the *takeover+influence* condition and the *takeover* condition. With the *takeover+influence* condition, 3 drivers intervened, while 3 also did so in the *takeover* condition (see Fig. 11). Performing a Chi Squared test (χ^2=0, df=1, p=1) we do not see a significant difference.

2) Comparison to Adult Demographic

When we compared the total rate of intervention between different demographics, we do see some significant differences. Compared to adults who experienced imperfect driving in Study 1, the high school drivers intervened just as much, with 1 more driver intervening (χ^2=0.125, df=1, p=0.723). However, we do see that seniors intervened significantly less than adults, with less than half as many drivers taking action (χ^2=6.4, df=1, p=0.011).

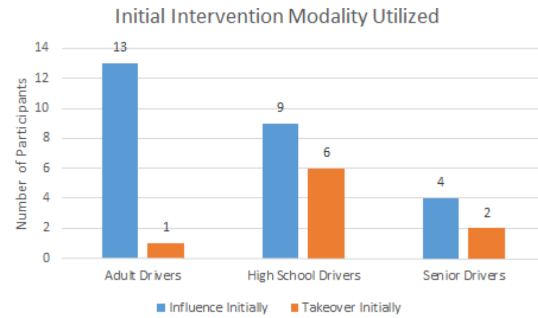

Figure 12: The initial intervention modality utilized for each of the three demographics that experienced imperfect driving.

Another interesting comparison can be made by looking at Fig. 12, which described the initial intervention modality utilized for every driver who intervened. We can see that both the high school drivers and senior drivers did not behave the same way as the adult drivers, who instinctively used the influence mode first. Many drivers in the other two demographics used *takeover* initially.

3) Self-Reported Attitudinal Data

Due to the low amount of intervention from the senior population, we were motivated to look into the post-drive questionnaire section that asked participants how they felt about the quality of the drive. One question asked participants how they felt when they drove, and the other asked how they felt when the automated driving system drove. A 5-point Lickert scale was used, where 1=very poorly and 5=very well. Comparing the responses, the seniors rated their driving performance during the experiment to be significantly worse than the automated driving system. Performing a paired t-test, we can see the strong difference (t=4.34, df=19, p<0.01).

Table 2: Self-reported attitudinal responses to driving quality (Seniors).

Question	Mean	Std. Dev.
When I was driving I felt that I drove…	2.80	0.768
I felt the automated driving system drove…	3.65	0.813

C. Discussion

The analysis above shows that there is not much difference in the number of interventions between the *takeover* and *takeover+influence* conditions for high school drivers. It was suggested that if they felt the need to intervene, the modality available to them did not make a significant difference. High school drivers would intervene with whatever modalities that were given to them. Unlike the adult population, the high school drivers still utilized *takeover* for many of the interventions initially. This might due to the fact that these drivers were less experienced and less comfortable with environments where they had less control. It appeared that they would rather be in a state of control than be in one of uncertainty. However, they did not necessarily intervene more. This could also be potentially due to inexperience, as a few participants noted that they were not aware of any poor driving by the automated driving system.

One of the interesting findings is the lack of intervention by the experienced senior drivers. It was expected that this demographic group would be most sensitive to the car's imperfect driving and would consequently intervene the most. From the post-drive interviews and questionnaire responses, all senior drivers indicated that they indeed noted that there were instances when the car's automated driving system performed poorly. However, many of the senior drivers still trusted the car and decided not to intervene. Furthermore, due to the steering wheel's handling, it was difficult for many seniors to drive as well as they would like. Even with the car's occasional weaving, many seniors still felt that the car had performed better than they were. So, the majority of senior drivers decided not to intervene. This can present troubling ramifications when a necessary handoff of control needs to occur with a senior who has trust and relies heavily on the automated driving system to perform.

Through testing these two demographic groups, another interesting finding is the drivers' intention to intervene. Several participants for both demographics (3 high school drivers and 4 senior drivers) in the *takeover* condition tried to initially influence the car. They did not realize that was not an option available to them (as they were not given the *takeover+influence* condition). Even though it was clear that their actions did not produce any result, they still tried hard to correct the car. For example, one participant kept turning the wheel to almost a 90 degree offset and kept it at that angle. It was clear that the steering wheel was actually decoupled from the control of the car, yet he continued trying anyways. This shows that drivers still view the steering wheel as a natural override that can be used to regain some control at any time.

VI. CONCLUSION

In this series of studies that investigated different driver intervention modalities, there are some significant results. In the first study, we noted that the adult driver population was very sensitive to the vehicle's movement and motions, particularly when the car's movement deviates from the ideal. During these instances of the vehicle's imperfect driving, the human drivers were readily willing to intervene as long as they could take on a more supervisory role and were not asked to immediately become the operator of the car. This feeling of not wanting to retake full responsibility appeared to be so strong that they were willing to tolerate brief instances of the vehicle's imperfect driving (if the only available solution for them was to fully takeover control again). Therefore, a form of shared control in this case is both desired and expected.

Another interesting insight we noted in our first study related to drivers' sleepiness. We observed that when the drivers experienced only *perfect driving* condition (where the car was always ideally in the center of the lane), they tended to exhibit more sleepy behaviors and were less vigilant than those drivers who experienced *imperfect driving* condition. For the drivers who were subjected to *imperfect driving*, they appeared to be more alert and constantly on the lookout for the car's unusual behaviors. While it is not good to have an automated driving system weave to keep drivers awake, this effect may be leveraged in a way that can keep human drivers more alert.

In our second study, we examined how different demographics would respond in the same driving scenario. We noted that the high school drivers intervened the most, while the senior drivers intervened the least. One important insight is that many senior drivers indicated that the car was still trustworthy and intervention was not necessary. They even thought that the car performed better than they did. Through gathering these insights, the researchers can develop better intervention modes and vehicle interfaces, which can improve driver comfort and road safety.

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