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Actions Speak Louder: Effects of a Transforming Steering Wheel on Post-Transition Driver Performance

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***Abstract*— For partially autonomous vehicles, the user interface conveys vital information to drivers and can greatly influence how drivers behave after a transition of control from automation. Conventional interfaces that use audio and visual channels are helpful, but are limited in effectiveness. In this paper, we explore the use of a transforming steering wheel interface to assist drivers in transitions of control. We conducted two studies evaluating the effects of this system on driver performance and user experience. The first is a quantitative controlled study examining driving performance after an abrupt loss of autonomous vehicle control. The participants (N = 56) experienced a simulated driving scenario that varied the behavior of the steering wheel (*transforming* and *non-transforming*) and the transition time (2 seconds and 5 seconds). Drivers who experienced the transforming steering wheel performed significantly better than those who experienced a non-transforming steering wheel. The second study is qualitative and exploratory, where interaction experts (N = 14) evaluated the transforming steering wheel using design improvisation. The findings of these two studies suggest that a transforming steering wheel can be utilized to better assist drivers in taking back control in future autonomous vehicles.**

Keywords—Controlled Study, Autonomous Driving Simulation, Transition of Control, Steering Wheel Interface, Human Factors

I. INTRODUCTION

In future autonomous driving systems, the vehicle's automation will be required to take on more functions and responsibilities. For example, in Society of Automotive Engineers' (SAE) levels of automation paradigm, vehicles with Level 3 automation will allow the system to execute the driving and monitor the environment [1]. However, drivers may still be required to act as the fallback and intervene in certain scenarios. Hence, it is imperative to design vehicles to give drivers the best possible opportunity to succeed during a transition of control. In particular, the user interface of the autonomous car is critical to this transition performance.

Currently, in vehicles with partial autonomy, the interface provides drivers with a visual alert on the instrument cluster as well as an audio alert when the automation relinquishes control. With this paradigm, it is expected that drivers may need some minimum amount of time to regain control and negotiate the upcoming situation on the road. However, current user interfaces may not provide the optimal experience for drivers. For example, audio and visual alerts alone may be too subtle to attract the attention of disengaged drivers. Thus, a stronger alert modality should be explored. Some interfaces also do not provide a clear indicator of what state the car is in or who is currently in control of the vehicle. So, if drivers experience a subtle transition, they may not immediately know that the car's automation is off. This may lead to drivers' hesitation and confusion. To address these areas of concern, we propose a new type of interface - the transforming steering wheel. This system provides an additional alert modality and transforms to reflect changes in control state. Utilizing these properties, the transforming steering wheel can help to improve driving performance and to reduce the minimum time drivers need for a transition of control.

Figure 1: A participant navigating the critical event successfully

In this paper, we describe the design and evaluation of a steering wheel interface that can physically transform to reflect the mode of automation. We prototyped this steering wheel to function in a high-fidelity driving simulator. The steering wheel was programmed to receive commands from the simulation software and to transform during a transition of control. We evaluated the transforming steering wheel interface using a controlled experiment (N = 56) to see whether it would improve performance of drivers after a transition of control in a partial automation driving context. To better understand the user experience issues associated with the transforming steering wheel movement, we also performed a qualitative study (N = 14) with interaction design experts. Using Wizard of Oz design improvisation with interaction experts, we varied the speed and style of the transformations to explore the properties of the motion afforded by this system [2]. These two studies help to demonstrate how our transforming steering wheel design can assist drivers of partially autonomous vehicles in safety critical situations.

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II. BACKGROUND

Currently, the best way to perform transitions of control in partially autonomous vehicles has not been determined. While industry standards, such as the SAE levels of automation [1], indicate that drivers must be given “sufficient time” for transition of control, this “time” has not been defined yet. Damböck et al. tested several takeover times and determined that post-transition driving performance appeared to plateau at 8 seconds [3]. Beukel et al. similarly found that longer advanced warnings led to more successfully avoided collisions [4]. In our prior research [5]–[7], very significant differences in post-transition performance were observed between the different transition time conditions (2, 5 & 8 seconds) tested.

Some studies in transitions of control focused on factors such as what might negatively affect the performance of drivers [8]–[13]. For instance, Gold et al. found that distracted drivers given shorter takeover request times tended to respond more quickly but exhibit worse performance [14]. Other studies looked at how driving performance could be improved through various design interventions. Researchers found that differences in alert mechanisms could reduce the transition time [15]. Unconventional alert modalities could also be used to affect performance: Melcher et al. utilized the physical movement of cars to inform the drivers that a takeover was necessary [16]. Petermeijer et al. found that vibrotactile stimuli is effective at providing a warning to drivers [17].

While the idea of transforming steering wheels has been featured in concept vehicles and videos from automotive companies such as BMW [18] and Nissan [19], there have only been a few studies examining how transforming steering wheels should be designed and how they affect drivers' performance. Recently, Kerschbaum et al. examined the effects of a mechanically transforming steering wheel, which changes shape by rotating quadrants of the steering wheel, on driving performance [20]. This study found no significant differences between the transforming and non-transforming conditions, but the results suggest that driving performance improvements are possible. As humans are very sensitive to movement [21], we believe that the design and magnitude of a transforming steering wheel's mechanical movement may be key to its effectiveness in assisting drivers.

Figure 2: Stanford Driving Simulator

III. SYSTEM

We created a transforming steering wheel system which extends and withdraws its steering handles when the car is in the manual or the autonomous driving mode, respectively. By harnessing the power of movement, we hypothesized that this steering wheel would not only provide a better alert for drivers, but would also act as a better indicator of control state, which could significantly reduce drivers' confusion. The retracted state of the steering wheel shows drivers that the autonomous driving mode is on. Conversely, when the steering wheel is deployed, it indicates to drivers that the manual driving mode is on and they need to take over the control of vehicles.

A. Simulator

This study took place in the Stanford fixed-base Driving Simulator (Figure 2), which has two components. The first is the vehicle chassis, a modified Toyota Avalon, which provides an immersive full car interface. To help improve the simulator's presence [22], haptic feedback is incorporated through a motor on the steering column and the pneumatic system attached to the gas/brake pedals. The Driving Simulator's other component is the large cylindrical projection screen surrounding the car, providing a 270-degree field of view. The videos of five projectors are blended together to create a seamless simulated driving environment. A sixth projector is used to display the rear view and LCD panels are installed in the side view mirrors. External speakers and a subwoofer help simulate environmental sounds, such as road noise. Several GoPro cameras are installed inside the car's cabin so that the drivers' behavior during the study can be monitored and recorded. Realtime Technologies' SimCreator software generates the simulation's audiovisual components.

B. Steering Wheel Development

To determine the form-factor and movement of the robotic steering wheel, we conducted several sessions of initial rapid prototyping and produced a variety of simple foam-core concept prototypes. Some examples can be seen in Figure 3. We also invited several interaction and interface experts to evaluate the prototypes and determine which concepts should be further developed. As the final prototype would be tested inside the full car driving simulator, concepts that required extensive modification to the steering column were avoided.

The robotic steering wheel concepts were evaluated against the following three main design requirements:

1. **Distinct Physical States -** The transforming robotic steering wheel needs to have two distinct physical states (retracted and deployed) to clearly indicate whether the human driver or the vehicle automation is in control. If the physical states of the steering wheel are too similar, drivers may become confused or act indecisively.
2. **Noticeable Movement -** The mechanical movement of the robotic steering wheel needs to be visibly prominent so that it can easily get the attention of drivers. If the movement is not pronounced, the effectiveness of the steering wheel as an alert mechanism may be reduced.

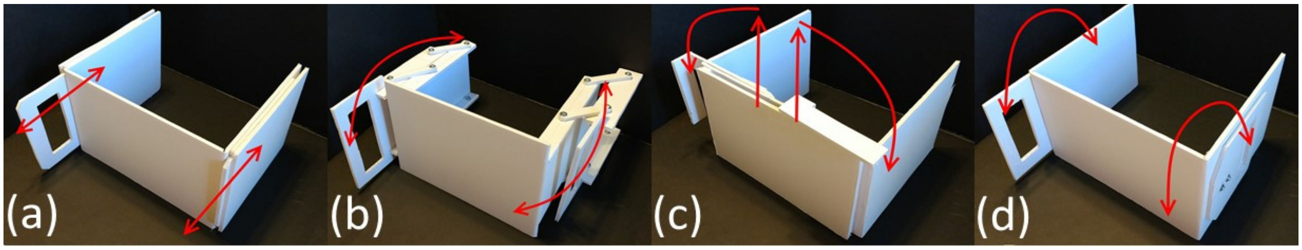

Figure 3: Initial foam-core prototypes examing four different types of transformation movements

3. **Indicating Transition of Control -** When the steering wheel is deployed, the movement needs to signal that control of the car is handed over to the driver. Similarly, when the steering wheel is retracted, the movement needs to indicate that the vehicle's automation is taking control.

Many concepts that we prototyped did not satisfy the first design requirement. For example, the conventional circular steering wheel concepts did not seem to the evaluators to have two distinctly different states. Particularly, they had retracted states which still suggested that the driver could exert agency. So, these concepts were viewed as less favorable in comparison to the two handles steering wheel concepts.

The evaluators found that more complex sweeping motions were better for satisfying the second design requirement. For instance, the concept in Figure 3a had a very simple in/out motion while the concept in Figure 3b had a more complex motion because of the four-bar linkage. While both movements appeared to be appropriate for a transforming steering wheel, the more complex motion contained movement along more than one axis and was thus more noticeable. So, this concept utilizing a four-bar linkage was favored by the evaluators.

The third design requirement favored designs that had the steering wheel move towards drivers when deploying and away from drivers when retracting. The steering wheel concepts that did not have this characteristic felt "unaccommodating" or "foreign" to the evaluators. For example, the concept in Figure 3c had very large radial movement, which the evaluators found odd. Some commented that it reminded them of an insect's antennae and did not produce the desired effects. Therefore, it was less preferred than the concept in Figure 3d, which appeared to the evaluators to have a simple handoff motion that was more natural and cooperative.

C. Final Prototype

The design of the transforming steering wheel final prototype was based on the two foam-core concepts that were most favored by the evaluators. This robotic steering wheel is composed of a center frame with two handles on each side. Each handle has both an upper and lower component, each independently actuated. When the steering wheel is in the retracted state, the components are separated from each other. However, they dock together when this robotic steering wheel is in the deployed state. The upper component is a part of the four-bar linkage design derived from the concept in Figure 3b. Similarly, the lower component is a part of the rotating design derived from the concept in 3d. This combination allows drivers to experience both a complex movement and a simple movement, which occur in different planes of motion. This gives the prototype a more noticeable transformation.

The frame of the steering wheel is constructed out of extruded 80/20 aluminum channels and laser cut acrylic sheets. This allows for greater flexibility in mounting and positioning various parts of this steering wheel. A 6-bolt short hub adaptor is used so that the robotic steering wheel can effectively apply torque. The steering wheel frame is attached to the short hub, which is mounted onto the spline of the steering column (Figure 4). The upper and lower components of the handles are 3D printed through a Stereolithography process on a Projet printer. The handle components are very dense and, thus, feel sturdy when grasped.

Four Dynamixel MX-28 Smart Actuators drive the movement of the handle components. These actuators allow for precise digital control of the actuator's speed, torque, and position over UART. The actuators' motions are orchestrated by the OpenCM 9.04M and the OpenCM 485 expansion

Figure 4: Final Transforming Steering Wheel Mounted in Driving Simulator. Retracted (a) and Deployed (b)

board. This controller features four dedicated Dynamixel TTL bus connectors for the smart actuators and a Serial Interface over USB. The expansion board, with its ability to accept a wide range of input voltages, allows for higher powered actuators such as the MX-28 to be used. The driving simulator is capable of sending commands to the transforming steering wheel. It does so via UDP to a node.js server running on a Raspberry Pi Linux-based single board computer. The Raspberry Pi communicates with an Arduino microcontroller in the steering column through a serial connection. This Arduino microcontroller interfaces with the steering wheel, interpreting the driving simulator's commands to provide the steering wheels with the appropriate actions to perform. The Interaction Engine, a framework for prototyping connected devices, is used as the starting point for the system [23].

IV. DRIVING PERFORMANCE STUDY - METHODOLOGY

A. Course

Over the course of the experiment, control of the car alternates between the participants and the automated driving system. The participants drive the car manually in certain segments, but the automated driving mode performs the majority of the driving task. As shown in Figure 5, this course is composed of three different sections. To allow the participants to practice and become acclimated to driving in the simulator, the first 5-minute section contains segments of road similar to those that the participants will encounter later in the drive. At the end of this first section, participants are asked to enable the automated driving mode. For participants experiencing the *transforming* condition, the steering wheel retracts when the enable automation button is pressed. The vehicle automation then drives in the second section for the next 10 minutes. While mostly composed of a long segment of straight road, this second section also contains several curves at the beginning to demonstrate that the automated driving mode is normally capable of negotiating many road types. This is important due to the design of the critical event.

At the beginning of the last section, the participants face an unanticipated driving challenge. The car approaches a curve, which lacks lane markings, and where construction is in progress (Figure 6). A set of pylons is placed to indicate where the center divider is located. Another set of pylons is used to close off the right lane (where an excavator is placed) and to force the participants to stay in the left lane. This area provides a realistic scenario which a vehicle's automated driving system may have difficulty negotiating in real life. As this scenario requires the participants to both comprehend the situation and then react accordingly, it is an appropriate test of participants' ability to regain control of the car.

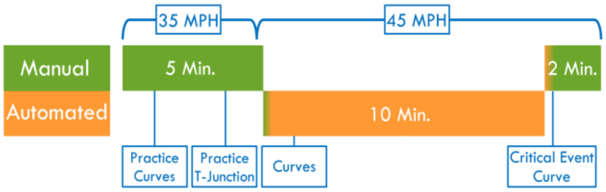

Figure 5: Diagram of the Simulated Driving Course

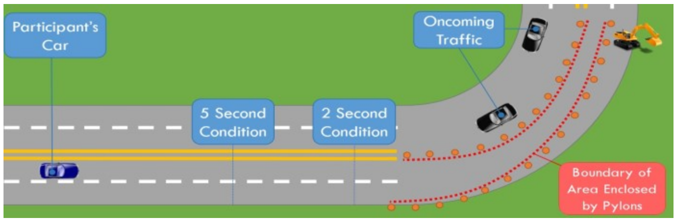

Figure 6: Diagram of the Critical Transition Event

Full control of the vehicle is returned to the participants a few seconds (i.e., 2 or 5 seconds) before entering this critical event. An audible alert: "Emergency, Automation Off" and a visual alert on the instrument cluster indicate that the unstructured transition has occurred. The control of the car is instantly given back to the participants in the drive mode, with the steering wheel centered, and with no additional input to the brake or throttle. Once the vehicle enters the curve, traffic is spawned in the two oncoming lanes to encourage the participants to stay between the pylons and not to take evasive actions in that direction. After the event, the participants drive manually for 2 minutes until the end of the course.

B. Transition Time Manipulation

The transition time is defined as the amount of time it takes for the car to reach the lane closure. The car consistently travels at 45 mph at the point of transition, and always enters the critical event in the left lane. Given the speed and lane position when transition occurs, the transition point for each time condition is placed at an appropriate distance from the pylons. For the results of this study to be compared with those of our prior research, 2 seconds and 5 seconds are chosen to be the two transition time conditions. In our previous research, an 8-second condition was also tested; however, every participant that experienced that condition always performed perfectly when traversing the critical event. Because of this ceiling effect, the 8-second condition is excluded.

C. Steering Wheel Behavior Manipulation

In this study, two steering wheel behavior conditions are tested. In the *transforming* condition, the steering wheel retracts when the automation is enabled and deploys when the automation is disabled. Conversely, in the *non-transforming* condition, the steering wheel remains deployed throughout the drive. Testing these two conditions helps to determine whether the physical movement from the steering wheel system's transformation has any effect on driver performance.

D. Procedure

Participants are first asked to sign a consent form and complete a pre-drive questionnaire. They are then led into the driving simulator room. To ensure that the participants will not be distracted during the drive, they are asked to relinquish their electronic devices during the study. They are also briefed on the vehicle's automated driving system and how to enable it. For those being assigned with the *transforming* condition, the participants are shown how the steering wheel looks like when the automation is in control (retracted) and when the driver is in control (deployed). Participants are not given a secondary task, so when the automated driving mode is enabled, they are only able to monitor the car's automation driving. To be able to compare with previous studies, the participants are not informed of the transition in advance and are not additionally incentivized to perform well in the driving task. Overall, the simulated driving task takes 15 to 20 minutes to complete. Afterwards, participants are asked to complete the post-drive questionnaire regarding their driving experience in the simulator. They are also asked about how they perceived the automated driving mode and steering wheel.

E. Participants

A total of 56 participants were recruited for this study with 14 participants in each condition. As they were recruited from Stanford University and other nearby communities, the participant pool had a diverse age distribution, which ranged from 18 to 81 years old (M = 36.5 years, SD = 18.5 years). The reported years of driving experience ranged from 1 year to 68 years (M = 19.5 years, SD = 19.4 years). This study had a gender distribution of 52% males and 48% females.

V. DRIVER PERFORMANCE STUDY - ANALYSIS

A. Driving Behavior Data

The driving data for this study, such as the driver's inputs and the vehicle's position/orientation, was collected from the simulator at 60Hz. The driving metrics were selected to examine how well participants performed on the curve. For the analysis of the data, Python was used to extract measures of driving performance and *R* was used to perform the various statistical tests. The following measures were calculated over the duration of the curve, with the start point where the curved section of the road began, and the end point at the end of the curve. For one of the participants, who did not traverse the entire curve because of the severity of their crash, only the driving data up until the stopping point was used for analysis.

1) Negotiating the Critical Event

While traversing the critical event, it was important for the participants to stay in the area that was enclosed by the pylons. We define the act of hitting the pylons as a road excursion. Additionally, due to incoming traffic and objects on the road, it was particularly hazardous if the entire car crossed over to the other side of the pylon wall. We define this act as a catastrophic road excursion. Performing Fisher's exact test on these two binary measures, we found no significant difference between the *non-transforming* and *transforming* conditions with regards to road excursion (p = 1). However, there was a significant difference with regards to catastrophic road excursion ($p < 0.05$). For the *non-transforming* condition, 6 of 28 participants had an excursion and could not successfully negotiate the event, with 5 performing catastrophic road excursions. On the other hand, only 5 of the 28 participants in the *transforming* condition failed, with no catastrophic road excursions. Also, all but 1 excursion occurred in the 2-second condition. Video analysis confirmed the above results.

2) Standard Deviation of Road Offset

The road offset is defined as the distance of the car from the centerline of the road. Verster et al. [24] and Brookhuis et al. [25] indicated that the standard deviation in road offset could be used as a measure of driving performance. Having a smaller standard deviation in road offset indicates that the driving is more stable, staying close to the ideal driving line. This measure is similar to the standard deviation in lane position, which is defined in SAE J2944 [26]. When control of the vehicle was returned to the participants on the straight stretch of road immediately before the critical event, the steering wheel was centered. Therefore, at the transition, there should not be any detrimental artifacts on the standard deviation of road offset caused by the steering wheel position.

Performing a two-way ANOVA on the standard deviation of the road offset (in meters) yielded a main effect for both the transition time ($F(1,52) = 9.03$, $p < 0.01$) and steering wheel behavior ($F(1,52) = 4.56$, $p < 0.05$). Conducting the Tukey HSD post-hoc analysis showed that there was a significant difference between the 5-second *non-transforming* (M = 0.305, SD = 0.102) and the 2-second *non-transforming* (M = 1.17, SD = 1.33) conditions ($p < 0.01$). There was also a significant difference between the 2-second *transforming* (M = 0.461, SD = 0.135) and 2-second *non-transforming* conditions ($p < 0.05$). However, there was no significant difference between the 5-second *transforming* (M = 0.251, SD = 0.09) and the 2-second *transforming* conditions (p = 0.84).

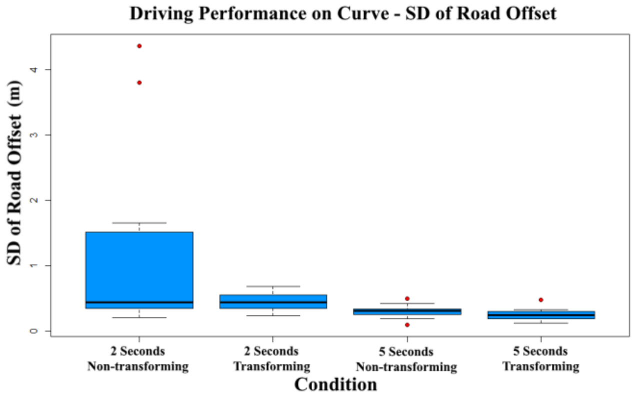

Figure 7: Road Offset Standard Deviation (in meters).

3) Standard Deviation of Steering Wheel Position

Another related metric that can be used to measure driving performance is the standard deviation of the steering wheel position (in radians) [25]. When performing the turn at the critical event, the standard deviation is expected to be small, as the steering wheel angle should be kept mostly constant during this stretch. Performing a two-way ANOVA on the standard deviation of steering wheel position yielded a main effect for transition time ($F(1,52) = 76.8$, $p < 0.001$), but not for steering wheel behavior ($F(1,52) = 1.0$, $p = 0.321$). The post-hoc comparison using the Tukey HSD indicated that the 5-second *non-transforming* (M = 0.180, SD = 0.0747) and the 2 seconds *non-transforming* (M = 0.670, SD = 0.274) conditions were significantly different ($p < 0.001$). Similarly, there was also a significant difference between the 5-second *transforming* (M = 0.208, SD = 0.0953) and the 2-second *transforming* (M = 0.547, SD = 0.188) conditions ($p < 0.001$).

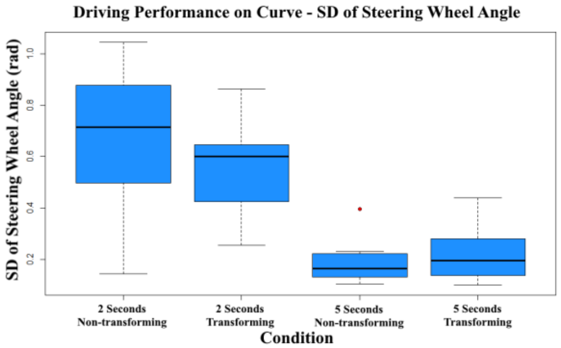

Figure 8: Steering Wheel Position Standard Deviation (in radians).

4) *Time to Evasive Action*

Time to evasive action is the amount of time from the transition until the participants either turn the steering wheel or step on the gas/brake pedals. This measure was not used in previous studies because it was not appropriate for evaluating performance differences between transition time conditions. For instance, the participants with a greater amount of transition time might negotiate the critical event perfectly, but respond slower as the event was further away. This metric, though, is useful for comparing the performance if the transition time is the same, but the steering wheel behavior is different. However, after performing paired t-tests, there was no significant difference between the *transforming* and *non-transforming* conditions for both the 2 seconds transition time ($p = 0.450$) and the 5 seconds transition time ($p = 0.291$).

B. *Comparison of Form Factor*

The form factor of the transforming steering wheel might have an effect on driving performance. To examine this, we compared the results from the *non-transforming* condition to those of our previous studies, in which a conventional steering wheel was used [5]. Conducting a two-way ANOVA, we did not see any significant difference for form factor in standard deviation of road offset ($F(1,44) = 0.30$, $p = 0.585$), standard deviation of steering position ($F(1,44) = 0.772$, $p = 0.382$), or time to evasive action ($F(1,44) = 2.37$, $p = 0.130$). To see if the transforming steering wheel performed better than the conventional steering wheel, we compared the results of the *transforming* condition. Conducting a two-way ANOVA yielded a main effect for the standard deviation of road offset ($F(1,44) = 9.94$, $p < 0.01$). So, participants in the *transforming* condition performed significantly better for this metric.

C. *Attitudinal Data*

Much of the post-drive questionnaire asked the participants how well certain words or phrases described the automated driving system. There were also additional questions that asked the participants how they perceived the steering wheel. A 7-point Likert Scale was used (1 = *describes poorly*; 7 = *describes well*) for most questions, but a few used a 10-point Likert Scale. Performing a two-way ANOVA test, several significant differences were found with regards to steering wheel behavior (see Table 1).

Table 1: Results of Post Drive Questionnaire

Question	**Results for Steering Wheel Behavior**
The Steering Wheel of the car provided insight on the automation's behavior.	$\boldsymbol{F(1,52) = 4.34}$ $\boldsymbol{p < 0.05}$
I felt the automated driving system in the car was (technical–human)	$\boldsymbol{F(1,52) = 14}$ $\boldsymbol{p < 0.001}$
When the car was in automated driving mode, I felt (anxious–calm)	$\boldsymbol{F(1,52) = 4.28}$ $\boldsymbol{p < 0.05}$

The participants of the *transforming* condition ($M = 3.75$, $SD = 1.78$) rated the steering wheel as providing more insight into the automation's behavior than the participants of the *non-transforming* condition ($M = 2.82$, $SD = 1.65$). In the *transforming* condition ($M = 2.64$, $SD = 1.19$), the automated driving system was rated as more technical / less human than in the *non-transforming* condition ($M = 4.11$, $SD = 1.66$). Finally, the participants in the *transforming* condition ($M = 7.07$, $SD = 2.99$) felt more anxious and less calm than those in the non-transforming condition ($M = 8.55$, $SD = 2.25$).

VI. DRIVER PERFORMANCE STUDY - DISCUSSION

From these results, we can see that the *transforming* steering wheel is more effective than the *non-transforming* steering wheel at motivating driving performance. While the participants who experienced the *transforming* steering wheel were not perfect, they had a significantly smaller standard deviation of road offset and significantly fewer catastrophic excursions. This indicated that while there were some crashes for participants in the *transforming* condition, they were much lower in magnitude. This also suggested that the participants were able to negotiate the road hazard in a safer manner. The video of the critical event confirmed these performance metrics. The participants with excursions in the *transforming* condition only grazed the pylons with the edge of the car. For the *non-transforming* condition, some participants found themselves in the same lane as oncoming traffic or hit the excavator. Compared to previous benchmarks (conventional steering wheel), participants of the *transforming* condition also had better results for standard deviation of road offset.

However, the effectiveness of the transforming steering wheel is not without some drawbacks. Some participants commented that the transforming steering wheel made them feel significantly more anxious. This might be attributed to the quickness of deployment. Since the components of steering wheel moved towards the drivers at full speed, participants might have been concerned that they would be hit or pinched, leading to increased feelings of nervousness. However, the high speed might have caused the participants to be more alert when the transition occurred, leading to a better performance.

In comparing the differences in driving performance between the two transition time conditions, we observed results similar to those of our previous studies. Participants in the 2-second condition always performed poorer than those in the 5-second condition for several measures: standard deviation of steering wheel position and excursion from the area bounded by the pylons. In the case where the steering wheel was *non-transforming,* the participants in the 2-second condition also had a greater standard deviation of road offset than those in the 5-second condition. These results reconfirm the findings of our prior studies, indicating the 2 seconds is not enough time, while 5 seconds is sufficient. However, when the steering wheel was *transforming*, the participants in the 2-second condition were no longer significantly worse than those of the 5-second condition for standard deviation of road offset. Combined with the fact that the 2-second *transforming* condition was also significantly better than the 2-second *non-transforming* condition, it suggests that the transforming steering wheel can help reduce the minimum transition time.

VII. TRANSFORMATION MOVEMENT STUDY - METHODOLOGY

To understand which aspects of the transforming steering wheel's movements are effective in improving driving performance, we conducted an additional qualitative and exploratory study in the driving simulator. We invited interaction and interface experts (N = 14) to experience the steering wheel in Wizard of Oz design improvisation sessions. The evaluators were shown the deploy and retract animations of the transforming steering wheel at different speeds and styles. Afterwards, the evaluators were asked to describe the movement that they experienced and comment on how each physical transformation of the steering wheel made them feel.

A. Animations

In this study, three different speeds (30%, 50% and 100% of the maximum speed) were used for the deploy and retract animation. The steering wheel also deployed and retracted in three different transformation styles. The first was the *default* deploy and retract, in which all four handle components would begin moving at the same time and at the same speed. Both handles for this transformation would be synchronized. The second style was the *staggered* deploy and retract. Each handle component would move at the same speed, but only one component moved at a time. Each component would first take turns moving into an intermediate position and then take turns moving to their final positions. The order in which components moved was from left to right, with the top handles moving first, followed by the bottom handles. For this transformation, the handles would complete the animation at different times. The final transformation style tested was the *stutter* deploy. Similar to the *default* deploy, both handles for this transformation would be synchronized. All four handle components would begin moving at the same time and at the same speed, but changed speeds during the transformation. The components would alternate moving at maximum speed and at 10% of maximum for equal periods of time.

VIII. TRANSFORMATION MOVEMENT STUDY - DISCUSSION

With the *default* deploy and retract animations, the expert evaluators commented that there was a tradeoff between utility and comfort with regards to the speed of the transformation. At the highest speed, the steering wheel was able to reach its final configuration the fastest. For a deploy, this gave the evaluators the ability to exert agency almost instantly, which was important in safety critical situations. Another benefit of the highest speed setting was that it could reduce some uncertainty during a retraction. As one evaluators noted, it could be unclear who was in control during the period when the transformation occurred. So, it is preferable to minimize this duration of time in order to reduce uncertainty.

However, some evaluators found the highest speed of the steering wheel to be quite uncomfortable. For the default deploy, multiple components of the steering wheel moved quickly toward the evaluators, which triggered an innately adverse reaction [27]. Several evaluators commented that the steering wheel resembled a jaw, which made them feel as though the steering wheel was performing an attack. The sound at the highest speed was another factor that contributed to the discomfort. The actuators emitted a high-pitched squeal during the transformation. Additionally, an audible clacking noise was produced when the steering wheel components docked together, which could be startling. While these properties might be uncomfortable to the evaluators, they were extremely effective in grabbing the attention of the evaluators during a transition. So, it may be desirable to embrace this discomfort if the goal of the steering wheel is purely utilitarian, to provide the drivers with the best chance to successfully negotiate hazardous driving scenarios.

When the *default* deploy and retract animation were used at the lower speeds, evaluators felt a greater sense of comfort. The movement was not only less aggressive, but was also more predictable. As one evaluators noted, at high speed, the transformation was almost complete by the time she could realize what was going on. However, at lower speed, she could see and predict the path that the handle components were taking. Another evaluator noted that this predictability also instilled a sense that this was a designed and intentional motion. At lower speed, the movement also appeared to be smoother and more natural. However, at these lower speeds, there was no longer a sense of urgency, which was undesirable when a transition was necessary. While many preferred the slower speeds, evaluators deemed them to be inappropriate for safety critical situations. Some evaluators also felt that at the lowest speed, the steering wheel just took too long to get into position. If they disabled automation, they expected to be able to exert control immediately and not have to wait.

With the *staggered* deploy, evaluators no longer found the maximum speed to be as frightening. Because of the intermediate states, the deploy did not appear as aggressive. One evaluator also pointed out that because the components were not moving in unison and instead one at a time, it appeared to be friendlier. The evaluators also described this transformation as more robotic and more entertaining than the *default*. However, it suffered from the same utility problems of a slower default deploy, not immediately providing agency. Also, many evaluators found the transformation to be more distracting as their attentions were being pulled towards four different areas. While some evaluators noted that this style could be used in a non-safety critical context, the *staggered* animations were overall considered to be undesirable. Of all the deploy animations though, the *stutter* deploy was the least successful. Most evaluators viewed the transformation as defective. However, evaluators noted that if the alternating speed was removed, with the deploy being fast for most of the animation and slow at the end, it would be more comfortable.

IX. CONCLUSION AND FUTURE WORK

The driver performance study has yielded significant results on how a transforming steering wheel system can help drivers improve performance after a transition of control from vehicle automation. Drivers who experienced the *transforming* steering wheel tended to negotiate the critical event better and had less catastrophic excursions compared to drivers who experienced the *non-transforming* steering wheel. The transforming steering wheel also appears to help reduce the minimum necessary transition time, as drivers in the 2-second condition no longer performed significantly worse than those in the 5-second condition. These results are quite different from our previous studies, as 2 seconds may be enough given the proper user interface and alert mode. The transformation movement study illustrated the importance of the steering wheel movement, the speed of the transformation, and the accompanying noise component. These findings show that transforming steering wheels can be viable and it should be considered for future autonomous vehicles. For future works, it is important to examine if other novel interfaces, such as a LED steering wheel, can produce similar effects and results.

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REFERENCES

[1] SAE International, "Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles," SAE International, J3016A.

[2] B. Mok, D. Sirkin, S. Sibi, D. B. Miller, and W. Ju, "Understanding driver-automated vehicle interactions through Wizard of Oz design improvisation," in *Proceedings of the International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*, 2015, pp. 386–392.

[3] D. Damböck and K. Bengler, "Übernahmezeiten beim hochautomatisierten Fahren." [Online]. Available: http://www.ftm.mw.tum.de/uploads/media/24_Damboeck.pdf.

[4] A. P. van den Beukel and M. C. van der Voort, "The influence of time-criticality on Situation Awareness when retrieving human control after automated driving," in *16th International IEEE Conference on Intelligent Transportation Systems (ITSC 2013)*, 2013, pp. 2000–2005.

[5] B. Mok, M. Johns, K. J. Lee, H. P. Ive, D. Miller, and W. Ju, "Timing of unstructured transitions of control in automated driving," in *2015 IEEE Intelligent Vehicles Symposium (IV)*, 2015, pp. 1167–1172.

[6] B. Mok *et al.*, "Emergency, Automation Off: Unstructured Transition Timing for Distracted Drivers of Automated Vehicles," in *Intelligent Transportation Systems (ITSC), 2015 IEEE 18th International Conference on*, 2015, pp. 2458–2464.

[7] B. Mok, M. Johns, D. Miller, and W. Ju, "Tunneled In: Drivers with Active Secondary Tasks Need More Time to Transition from Automation," in *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, 2017, pp. 2840–2844.

[8] A. Borowsky and T. Oron-Gilad, "The effects of automation failure and secondary task on drivers' ability to mitigate hazards in highly or semi-automated vehicles," *Adv. Transp. Stud.*, no. 1, 2016.

[9] T. Ito, A. Takata, and K. Oosawa, "Time Required for Take-over from Automated to Manual Driving," 2016.

[10] J. Radlmayr, C. Gold, L. Lorenz, M. Farid, and K. Bengler, "How traffic situations and non-driving related tasks affect the take-over quality in highly automated driving," in *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 2014, vol. 58, pp. 2063–2067.

[11] K. Zeeb, A. Buchner, and M. Schrauf, "What determines the take-over time? An integrated model approach of driver take-over after automated driving," *Accid. Anal. Prev.*, vol. 78, pp. 212–221, May 2015.

[12] T. L. Louw, G. Kountouriotis, O. Carsten, and N. Merat, "Driver Inattention During Vehicle Automation: How Does Driver Engagement Affect Resumption Of Control?," 08-Oct-2015. [Online]. Available: http://eprints.whiterose.ac.uk/91858/.

[13] F. Naujoks, C. Purucker, and A. Neukum, "Secondary task engagement and vehicle automation–Comparing the effects of different automation levels in an on-road experiment," *Transp. Res. Part F Traffic Psychol. Behav.*, vol. 38, pp. 67–82, 2016.

[14] C. Gold, D. Dambock, L. Lorenz, and K. Bengler, "'Take over!' How long does it take to get the driver back into the loop?," *Proc. Hum. Factors Ergon. Soc. Annu. Meet.*, vol. 57, no. 1, pp. 1938–1942, Sep. 2013.

[15] P. Bazilinskyy, S. M. Petermeijer, V. Petrovych, D. Dodou, and J. C. F. De Winter, *Take-over requests in highly automated driving: A crowdsourcing survey on auditory, vibrotactile, and visual displays*. Unpublished, 2015.

[16] V. Melcher, S. Rauh, F. Diederichs, H. Widlroither, and W. Bauer, "Take-Over Requests for Automated Driving," *Procedia Manuf.*, vol. 3, pp. 2867–2873, Jan. 2015.

[17] S. Petermeijer, S. Cieler, and J. C. F. de Winter, "Comparing spatially static and dynamic vibrotactile take-over requests in the driver seat," *Accid. Anal. Prev.*, vol. 99, Part A, pp. 218–227, Feb. 2017.

[18] BMW Group, "The Next 100 Years - Brand Visions." [Online]. Available: https://www.bmwgroup.com/en/next100/brandvisions.html.

[19] Nissan USA, "Nissan IDS Concept: Nissan's vision for the future of EVs and autonomous driving," *Nissan Online Newsroom*. [Online]. Available: http://nissannews.com/en-US/nissan/usa/releases/nissan-ids-concept-nissan-s-vision-for-the-future-of-evs-and-autonomous-driving.

[20] P. Kerschbaum, L. Lorenz, and K. Bengler, "A transforming steering wheel for highly automated cars," in *2015 IEEE Intelligent Vehicles Symposium (IV)*, 2015, pp. 1287–1292.

[21] G. Hoffman and W. Ju, "Designing Robots With Movement in Mind," *J. Hum.-Robot Interact.*, vol. 3, no. 1, pp. 89–122, Mar. 2014.

[22] W. A. IJsselsteijn, H. de Ridder, J. Freeman, and S. E. Avons, "Presence: concept, determinants, and measurement," 2000, vol. 3959, pp. 520–529.

[23] N. Martelaro, M. Shiloh, and W. Ju, "The Interaction Engine: Tools for Prototyping Connected Devices," in *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction*, New York, NY, USA, 2016, pp. 762–765.

[24] J. C. Verster and T. Roth, "Standard operation procedures for conducting the on-the-road driving test, and measurement of the standard deviation of lateral position (SDLP)," *Int. J. Gen. Med.*, vol. 4, pp. 359–371, May 2011.

[25] K. A. Brookhuis, G. de Vries, and D. de Waard, "The effects of mobile telephoning on driving performance," *Accid. Anal. Prev.*, vol. 23, no. 4, pp. 309–316, Aug. 1991.

[26] SAE International, "J2944: Operational Definitions of Driving Performance Measures and Statistics - SAE International." [Online]. Available: http://standards.sae.org/j2944_201506/.

[27] C. K. Hsee, Y. Tu, Z. Y. Lu, and B. Ruan, "Approach aversion: Negative hedonic reactions toward approaching stimuli.," *J. Pers. Soc. Psychol.*, vol. 106, no. 5, p. 699, 2014.