Looking Ahead: Anticipatory Interfaces for Driver-Automation Collaboration

Mishel Johns*, Brian Mok*, Walter Talamonti Jr.†, Srinath Sibi* and Wendy Ju*
*Stanford University, Stanford, California. Email: {mishel, brianmok, ssibi, wendyju}@stanford.edu
†Ford Motor Company, Dearborn, Michigan. Email: wtalamo1@ford.com

***Abstract*—Partially automated driving systems that require driver supervision and intervention need to keep the driver in the loop and help maintain their situation awareness of the vehicle's current state and future plans. In this paper, we introduce the idea of an "Anticipatory Control Interface" - an interface that informs the driver of the lateral trajectory plan of the automated driving system. Our first prototype performs this task by actuating the steering wheel (physical) in advance of road wheel movement. A second prototype uses LEDs on a steering wheel cover to create a virtual steering wheel (visual) that can move in advance while keeping the steering wheel locked to the road wheel.**

We report an evaluation of the Anticipatory Control Interface prototypes based on their ability to support driver recognition and response to automation failures, compared to a control condition. Results show faster disengagement of automation and subsequently better takeover quality on failure with the physical anticipatory interface compared to the control.

I. Introduction

Road vehicle automation is a rapidly advancing field. Automation features range from simple longitudinal and lateral control support systems like current-day adaptive cruise control and lane-keeping to full automation systems in the future where a driver might not be required to be engaged in the task of driving at all times. Current day semi-autonomous vehicle automation features such as adaptive cruise control exist for comfort, safety and convenience, but still depend on the driver to intervene and take responsibility if mishaps should arise. It is important to keep drivers in the loop and to inform them about what the car perceives and what it plans to do so they can safely intervene when necessary. The steering wheel is a natural location for an interface supporting shared lateral control between the driver and the automated vehicle.

In this paper, we explore driver-automation collaboration through the design and benchmarking of two "Anticipatory Control" steering-wheel prototypes that inform the driver of the impending steering action about to be taken by the automated driving system.

While a variety of algorithmic planning approaches are used by automated vehicle systems for different road situations [1], most approaches allow the control inputs for the short term (~5 seconds) future to be predicted unless sensor inputs change rapidly and unexpectedly. This allows us to actuate the steering wheel in advance of the road wheel in order to give the driver advance warning of the steering actions of the system and perhaps give them more time to react to the action if necessary. Such a pre-warning of the steering action of the automated driving system might allow drivers to better predict the actions of the system, supporting quicker recognition of and response to mistakes and increased trust in the system.

Fig. 1. Physical Anticipatory Steering system - the steering wheel turns before the vehicle does as it moves into the curve

The "Physical Anticipatory Steering" interface prototype described in this paper moves the steering wheel to show the road wheel angle an advance time of 1 second into the future. The "Visual Anticipatory Steering" interface moves a virtual steering wheel pattern on an LED steering cover instead to show future road wheel position, while keeping the physical steering wheel locked to the current angle of the road wheel.

These prototypes were tested in a driving simulator environment. We describe each prototype system design and reflect on the advantages and potential downsides for each design in supporting driver-automation interaction. The two prototypes were initially evaluated by the research team with a short drive for each prototype in the driving simulator. This evaluation allowed us to identify opportunities and flaws in each of the three prototypes, and to iterate on the design and settle on optimal values for design parameters.

A controlled evaluation was then conducted to benchmark drivers' ability to recognize system errors while using these two prototypes, in comparison to using an automated driving system with no anticipatory control interface.

II. Related Work

User interface design in vehicles has been changing at a rapid pace over the last few years. Driver assistance systems warn or support the driver of upcoming conditions or maneuvers, increasing the amount and complexity of information that the driver needs to process. This is especially true in partially automated driving systems, where the driver is not actively driving, yet needs to be aware and ready to intervene despite

978-1-5386-1526-3/17/$31.00

the automated system offering to take over more aspects of the driving task.

A. *Driver-Automation Collaboration*

Communication requirements between the driver and the automated system vary based on the capabilities of the automated driving system and the responsibilities of the human driver. An automated vehicle (SAE J3016 Levels 1-4) [2] should provide information to the driver when active and also accept input from the driver through the controls, at least in certain situations. Often, driver support information is displayed using visuals on a screen or even in a head-up display [3]. While these types of displays are effective at communicating complex information, they are physically separate from the driver controls, thus requiring additional cognitive steps to process that information and, when necessary, execute corrective action.

Most automated vehicle systems and presently available steering systems such as active lane-keeping transition control between automated and manual mode through the press of a button, or physical contact with and rotation of the steering wheel [4]. Such implementations work on the assumption that the vehicle is fully controlled either by the driver or by the automated system. Some researchers, such as Donald Norman, argue that this clear delineation of control is the only safe way to operate autonomous vehicles [5]. Sheridan's model of supervisory control [6], however, suggests that aspects of control should be split; the car should take care of normal driving activity, and the driver should monitor the system and surroundings for unexpected changes and make short discrete changes as needed. Shared control models, in contrast, have both the human and the automated system simultaneously sharing the active control of systems [7]. Such systems might be able to control the vehicle to follow the driver's input as closely as possible while staying within constraints applied due to vehicle limitations or safety reasons [8]–[10].

For both models of joint driver-automation control, successful joint action requires the vehicle to communicate both what it perceives and its plan of action. It should also inform the driver what automated features are enabled, which functions are being controlled by automation, and which remain in the control of the driver [11]. Seppelt et al. show that displaying the state of an adaptive cruise control system improved driver responses to events that exceeded the limits of the automated braking system, and suggest that drivers should be provided continuous information about the state of the automation [12].

B. *Steering Wheels as Displays*

The steering wheel acts not just as an interface for the driver to control the vehicle, but also as a display of the vehicle's current state. In addition, information on the actions of automation can also be displayed on the steering wheel in a shared control driving systems. A popular implementation of this is haptic shared control [7], [13], [14], where the automated driving system applies a torque to the steering wheel that the driver can choose to permit or to resist. The advantage of using the steering wheel for shared control with automation is that it is intuitively associated with lateral control of the vehicle, and the steering action by the automated system can be readily felt [4]. In these systems, the steering wheel is acting not just as an interface for the driver to control the vehicle, but also one for the vehicle to display its actions to the driver. Such systems, however, only communicate the present actions of the automated system, and not its plans for actions in the future.

Our prior work suggests that more nuanced haptic gestures cannot be utilized by the automated system on the steering wheel while maintaining a constant steering ratio and coupling between the steering wheel and the road wheel [15]. While the maintenance of such coupling seems intuitive, Kershbaum et al. [16] showed that for small angles, most drivers do not notice the decoupling of the steering wheel from road wheel angle, especially with a prototype steering wheel lacking visible spokes for visual orientation. In a steer-by-wire system where the steering wheel is not mechanically linked to the road wheel angle (such systems are found in newer high end vehicles, it is possible to decouple the steering wheel movement from the road wheel angle [17].

III. SETTING: DRIVING SIMULATOR

The designs under evaluation were implemented and tested in a full-car high-immersion driving simulator with a 24-foot diameter 260 degree cylindrical screen, a projected rear view and LED instrument clusters and side mirrors. The car contains instrumented vehicle controls and steering wheel buttons, and the vehicle dynamics simulation runs at 900Hz to simulate vehicle motion and provide realistic torque feedback to the steering wheel through a DC motor. Visual scenery and traffic scenario are simulated and refreshed at 60Hz.

The driving simulator has an automated driving mode through which the car can be programmed to drive under varying levels of automation and driver intervention. As the designs discussed here are intended for driving systems that are SAE Level 2 and above, the car is capable of following lanes, making turns at intersections and interacting with other simulated traffic. The steering wheel can be programmed to move according to the car's movements.

IV. PROTOTYPE 1: PHYSICAL ANTICIPATORY STEERING

A. *Motivation*

Gaze studies have shown that drivers tend to look at the spot where they intend the vehicle to go before they actually perform navigation actions. When negotiating a curve, drivers look at the tangent point of the curve about 1 second ahead of entering the curve [18]. Such an anticipatory gaze orientation occurs not only in driving, but also in locomotion [19]. It is possible that such gaze movements allow passengers in a vehicle to predict the actions of the driver. Our Physical Anticipatory Steering interface explores the idea of the steering wheel acting as the 'gaze' of the car, giving a preview of the projected trajectory to the driver in the vehicle as well as directing the attention of the driver.

Automated vehicle algorithms use various planning approaches for different road situations [1], and in many of these cases, the control inputs for the short term future can be predicted. In the virtual world of our driving simulator, we have complete control over the environment, making it possible to actuate the steering wheel in advance of vehicle movement.

A system that moves the steering wheel in advance of vehicle steering movement might give drivers more time to react. Balachandran et. al. [20] showed that a haptic torque assisted steering system can improve driver reaction times to obstacles on the road. While the paper looked at applying torques to a driver-controlled steering wheel based on predicted trajectory feasibility, the results suggest that the Physical Anticipatory Steering interface for an automated vehicle might also improve driver reaction times.

B. Design

We designed a driving simulator model where the steering wheel moved 1 second in advance of the road wheels (See Figure 1). The Stanford Driving simulator is capable of playing back a recorded drive scenario. Steering angle data from one drive was captured to file and was used to actuate the steering wheel in advance during later drives using a PID controller. The simulated road wheel angle is also played back, and is not affected by torques applied to the steering wheel when automation is engaged.

C. Initial Impressions

The physical anticipatory steering wheel prototype was tested in the driving simulator with a short highway drive with multiple lane changes, and on a 25mph road with curves.

The non-intuitive breaking of coupling between the steering wheel and the road wheel was most obvious to the driver on low speed roads and turns in the simulated world that required larger steering wheel movements. At higher speeds and on highways, this decoupling was less noticeable. This matches observations from Philipp Kerschbaum's experiment using a steering wheel decoupled from the road wheels when automation is enabled [16].

The effect of the physical anticipatory steering wheel movement is quite subtle when changing lanes at highway speeds, as the angular movement of the steering wheel is quite small. Such a small movement is easily perceptible when the steering wheel is being held, but is not very visually noticeable when the driver does not have their hands on the wheel. One possible solution is to magnify the movement of the steering wheel only when it is not being held.

A one-second advance time was chosen for being large enough to be noticed, but small enough to be easy to link to the ensuing movement of the vehicle and not cause confusion.

We found that responding to user input with this interface is challenging and deserves further study - the steering wheel and the road wheel might not be at the same position when the driver choses to intervene. When a driver turns the steering wheel, the system needs to decide how to move the road wheel, and what torque to apply to the steering wheel. Switching over to full manual control immediately when the steering wheel is turned creates a jerk in vehicle movement as the road wheels start moving towards the position of the steering wheel and road torque starts being fed into the steering wheel. This might not allow a safe handover of control when the road wheel and the steering wheel positions are not in sync.

Fig. 2. The Visual Anticipatory Steering wheel, showing the virtual steering wheel pattern.

One possible solution is to time-shift the driver input similar to the automation steering display (1 second, in this case), and gradually speed it up to sync up to normal driving. Such an implementation would need to speed up to full coupling fairly quickly if the driver is to be able to react to an emergency. A slow time-shift would cause driver confusion and perhaps overcompensation as the vehicle does not react immediately to their input and drivers turn the steering further.

The prototype used for the study utilized a rapid change in road wheel angle, where the road wheel was moved as fast as possible to the position indicated by the steering wheel when a driver intervention was detected.

V. HMI Prototype 2: Visual Anticipatory Steering

A. Motivation

We realized while testing the physical anticipatory steering system that the biggest challenge was designing the takeover of control from the system, due to the possibility of mismatch between steering wheel angle and road wheel angle. An alternative solution, we found, was to show the anticipatory steering wheel position using a *virtual steering wheel* that was created by a pattern of LEDs on the wheel, as it lets us keep the steering wheel and the road wheel coupled.

B. Design

The Visual Steering wheel concept involves using a steering wheel cover with strip of LEDs around edge as a display of anticipatory steering information.

An individually addressable LED strip with 144 LEDs/meter based on the SK6812 control circuit from Adafruit Industries was mounted in a black faux-leather 15 in. diameter steering wheel cover with 179 LEDs on the circumference. The LED strip is mounted under the surface of the steering wheel cover, with holes punched in the surface to let the light through. Updating the lighting takes 30 µs for a single pixel and 5.2 ms to refresh the entire strip.

The driving simulator sends steering angle data via UDP over a wired Ethernet network at 100 Hz to a node.js server running on a Raspberry Pi 2 Linux-based single board computer running Raspberry Pi Debian Operating System Jessie. The computer communicates with an Arduino microcontroller over a serial connection at 115200 baud via a 3.3V to 5V level shifter, routed through the steering wheel clock spring.

The angle of the visual steering wheel is made independent of the angle of the steering wheel by compensating for the movement of the wheel. The virtual steering wheel shows the anticipatory steering angle, while the physical steering wheel remains coupled to the road wheel.

C. Initial Impressions

The Visual Anticipatory steering wheel interface allows us to show rotational information visually on the steering wheel. Implementing such a system on a production vehicle will require additional connections through the clock spring, including a high-amperage line for the LED power.

The Visual Anticipatory steering wheel prototype has the advantage of being contained in a steering wheel cover, and of being bright and easy to see. Care needed to be taken to get the brightness of the LEDs right - too dim and it was hard to see, too bright and it would be annoying or blinding for the driver. Since the LEDs are fairly small, we needed to put plastic tubing in to disperse the light and to increase the lighted area visible to the driver.

Alternate methods of displaying such visual information on the steering wheel include a projection from above, or mounting a screen on the steering wheel. However, these designs have disadvantages–a projector would project onto the driver's hands on the wheel as well, and a screen is bulky and expensive to shape to mount on a circular steering wheel. Another possible design involves a rotating physical attachment on top of the steering wheel that can act as the virtual wheel and requires only a single servo motor to rotate and show anticipatory steering movement.

The Visual Anticipatory steering wheel prototype allows us to scale up the anticipatory steering angle displayed in order to make movements more noticeable. However, that could confuse the driver's perception of the steering wheel movement required for their desired trajectory, and so such a scaling was not implemented in the prototype used in the evaluation.

VI. Study Design

We performed a controlled study comparing the effect of anticipatory steering systems on driver trust and driver recognition of automation errors. In addition, we looked at the effect of instructing the driver to keep their hands on the steering wheel. This led to the design of a 3x2 between-subjects study, with the system design (physical, visual anticipatory steering or control) and driver instruction (hands on/off the steering wheel) as the independent variables.

A. Hypotheses

Based on preliminary testing with the prototypes, we started out with the following hypotheses:

- Both the Physical Anticipatory steering system and the Visual Anticipatory steering system would allow drivers to react faster to automation failure than drivers in the control condition
- The Physical Anticipatory steering system would produce worse takeover performance than the Visual anticipatory steering system because of the possibility of mismatch between the road wheel angle and the steering angle at the time of transfer of control.
- The Physical anticipatory steering system would produce faster reaction times in the Hands-on condition because drivers can feel a movement on the steering wheel faster than they can see it.
- The Visual anticipatory steering system would produce faster reaction times in the Hands-off condition because drivers can notice movement in the bright LED pattern faster than they notice the unlit steering wheel move.

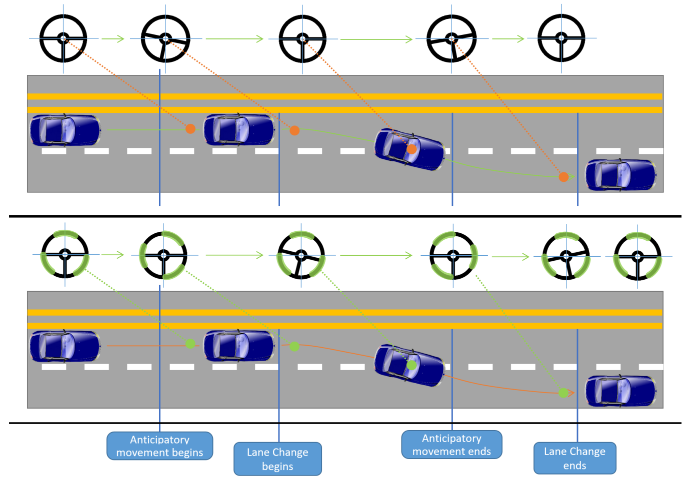

Fig. 3. An illustration of anticipatory movement, showing the movement of the steering wheel or the virtual steering wheel during a lane change, for the Physical Anticipatory Steering system (top) and the Visual Steering system (bottom). Time and road position are on the horizontal axis, and the dotted lines indicate that the anticipatory steering angle displayed matches the road angle 1 second later.

B. Automated Driving System Design

The automated driving system follows the centerline of the road and can be disabled using buttons on the steering wheel. Hitting the brakes (more than 5%) or turning the steering wheel (by applying a certain threshold torque) also disables automation immediately. In this study, automation is enabled automatically at specific locations on the course. This maintains consistent experimental conditions across study participants. The current state of automation (Enabled or Disabled) is indicated via and icon on the instrument cluster.

C. Driver Instructions

Participants are told that they will be driving a partially automated vehicle, and that they are responsible for vehicle safety at all times during the drive. They are informed about the prototype anticipatory systems they are using, and also told to either keep their hands off or on the steering wheel. In addition, they are informed of the three ways to disable automation (button press on the steering wheel, hitting the brakes, turning the steering wheel).

D. Driving Course

A simulated highway driving course, about 15 minutes long, is used to create scenarios where the drivers might feel the need to take over from automation. An initial practice course segment, with a 600m diameter banked 90-degree highway curve and a forced lane change due to lane closure, allows the participant to get used to driving in the simulator.

Automation is then enabled, and the vehicle drives itself through one leftward and one rightward lane change, another 600m diameter banked 90-degree highway curve and also brakes automatically for an erratic driver that cuts in front of it. At these four events, we check if the driver takes over control. We expect that the drivers using the anticipatory systems should be able to know 1 second in advance that the vehicle will turn and make the lane change/curve, and should thus take over less. The response to the car cutoff is that of braking, and the anticipatory steering systems are able to provide no pre-warning. The driver choice to take over or to trust the system at that point might be indicative of how much the system has earned their trust.

In the final 'exit' event, drivers face an automation failure. The automated driving system makes a mistake as it is unable to detect the lane markings and follows another car off the highway onto an exit ramp even though it is supposed to stay on the highway (see Figure 4). The drivers are told to stay on the highway, both in the initial instructions given to them, and in an audio prompt 12s before the event. We measure if the driver recognizes the mistake and takes over, how long they take to do it, what method they use to disengage automation and how they fare after takeover.

E. Questionnaire

Participants completed a questionnaire on a computer outside the driving simulator before and after their drive. The pre-drive questionnaire collects data on participants' age, gender and driving experience. The post-drive questionnaire asks participants to evaluate the prototype user interface on a 5 point Likert scale from strongly disagree to strongly agree with certain adjective. The adjectives used included "Useful", "Helpful", "Trustworthy", "Annoying", "Frightening", "Misleading", and "Confusing".

F. Behavioral Measures

All driving data is collected at 60Hz, and the data is analyzed using Python to extract measures of interest; R is used for statistical analysis. Events on the course are marked in the data in order to time driver reactions. We look at how often the drivers choose to take over during the course prior to the automation failure. This might indicate the level of trust or confidence they have in the automated system and the user interface. The primary measures we are interested in, however, are around the automation failure at the exit event.

We are interested in:

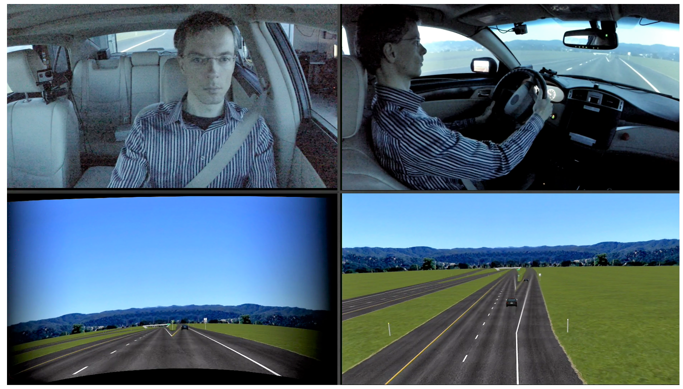

Fig. 4. The exit event - the driver switches off automation by steering the vehicle back on the highway after he recognizes that it is making a mistake.

- Whether the driver recognized the mistake made by automation and reacted appropriately by switching off automation and staying on the highway
- Driver reaction time: How long did it take drivers to switch off automation, for those who did react
- Driver reaction type: Method of switching off automation - button on the steering wheel, steering wheel torque or braking
- Quality of Driver takeover: How far did the driver move into the exit and off the right lane before veering back into to highway
- Quality of Driver takeover: Steering reversals from the start of event to the end of event

For the exit event, the 'event start time' is defined as the point where the road wheels start turning to take the vehicle off the highway. In the anticipatory steering conditions, the steering wheel or the visual pattern moves 1 second in advance of the event start time.

G. Participants

60 adults (Age mean = 43.3 years, S.D = 21.52) with a valid driver's license participated in the study. They had a driving experience of an average of 24.9 years, S.D of 21.82 years. There were 40 male and 20 female participants who took part in the study, and they were randomly assigned to conditions.

VII. Results

The results shows an improvement in performance in the physical anticipatory steering condition in comparison to the controlled condition.

Most participants were successful in recognizing the mistake made by the automated driving system at the highway exit and taking over to stay on the highway. Only 6 participants (out of 60) allowed automation to stay on and take the exit.

Figure 5 shows the takeover reaction time - the time from when the road wheel starts turns to move the vehicle off the road to when the driver turns off automation (if they do). Negative values are possible, as in the Anticipatory steering conditions, the steering wheels start moving one second earlier.

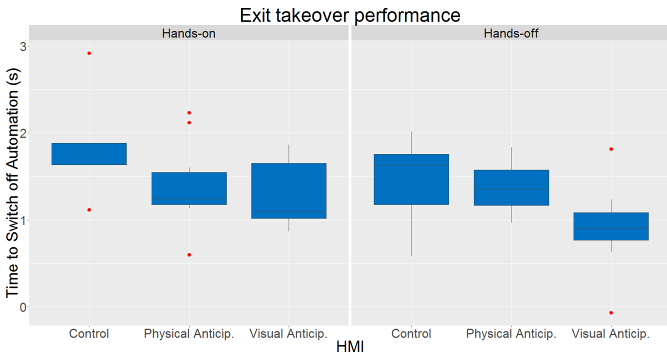

Fig. 5. Exit takeover reaction time. Box plots have a box from the 1st to 3rd quartile, the center line shows the mean, whiskers extend from the box to the furthest point within 1.5*interquartile range, and outliers are marked with a red dot.

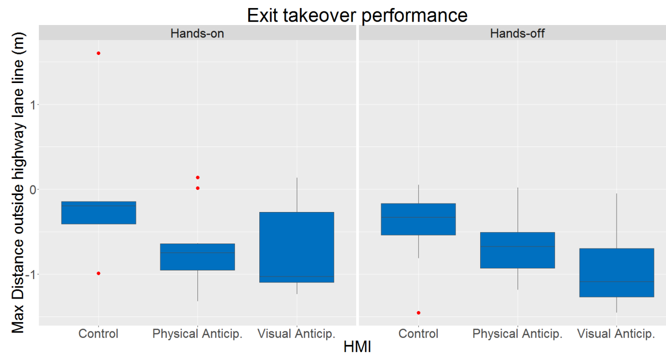

Fig. 6. Exit takeover quality

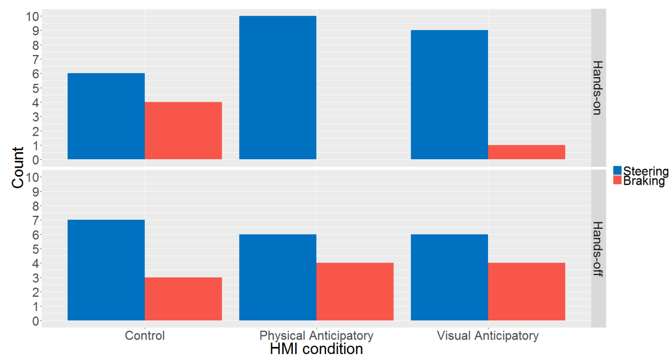

Fig. 7. Automation Disable Method at exit - Counts

Larger values show worse performance. Some drivers took over from automation before they could possibly have known about the automation failure, and their data was excluded from this analysis. These are probably due to the drivers anticipating a problem as soon as automation starts following the exit vehicle, even before it takes the exit.

A two-way between-subjects ANOVA was conducted to compare the effect of the HMI and the hand-on-wheel conditions on the takeover reaction time. There was a significant effect of HMI on takeover reaction time at the p¡0.05 level [F(2,40) = 3.77, p = 0.03]. The effect of the hands-on condition was not significant at the p¡0.05 level [F(1,40) = 2.948, p = 0.094]. The interaction between the two independent variables was not significant. A post-hoc Tukey multiple comparisons of means showed a significant difference between the Physical Anticipatory system (M = 1.12s, S.D = 0.49s) and the control condition (M = 1.61s, S.D = 0.56s) (p = 0.03, difference of means = 0.485s).

Figure 6 shows the takeover quality, as measured by the maximum distance moved off the lane. Participants who turned off automation before the event and those who allowed automation to take the exit were excluded from this analysis. A negative value indicates that the center of the vehicle did not cross the lane boundary, and larger values indicate worse performance. A two-way ANOVA showed a significant effect of HMI [F(2,39) = 3.19, p = 0.05] on takeover quality. A post-hoc Tukey multiple comparisons of means showed a significant difference between the Physical Anticipatory system (M = -0.79m, S.D = 0.51m) and the control condition (M = -0.29m, S.D = 0.7m) (p = 0.05, diff. of means = 0.50m).

No significant effects were found on the number of steering reversals in a 10 second period following the exit event.

An analysis of the method used to disable automation showed that not a single participant pressed the button to turn automation off at the exit event - all chose to either hit the brakes or turn the steering wheel. Figure 7 shows that more participants used the steering to turn off automation in the hands-on condition, but this effect is not statistically significant (Fisher's Exact Test for Count Data, p = 0.125).

Intervention was not common in the other events prior to automation failure at the exit (curve, lane changes etc). There seem to be slightly more interventions when the driver has their hands on the wheel (10 participants who intervened at least once in the hands-on condition vs 6 in the hands-off condition), but there is no statistically significant difference.

The survey data (collected as a Likert scale measurement as described earlier) was also analyzed. A two-way ANOVA showed that participants in the hands-off conditions found the User Interface to be significantly more 'Useful' (p¡0.02). However, the other measures ("Helpful", "Trustworthy", "Annoying", "Frightening", "Misleading", and "Confusing") showed no significant effect of the conditions.

VIII. Discussion

The results of our study show significant improvement between the physical anticipatory steering and the control conditions. However, no significant differences were found between the visual anticipatory steering and the control conditions. This could potentially be because drivers have a mental model of the steering wheel and its correspondence to vehicle movement. It is possible that the motion of the virtual LED pattern did not map as easily to road wheel movement over the course of our single session study. A longer learning period might allow drivers to build a subconscious association that supports faster recognition and reaction.

We expected the sudden change in road wheel angle at takeover of control in the anticipatory steering condition to reduce the quality of takeover, but that did not happen. The vehicle is traveling straight ahead before it starts taking the exit, so the change in angles between the steering wheel and the road wheel were not large enough to cause a disruption in the takeover.

The hypothesis that participants in the hands-off condition would do better with the Visual anticipatory steering HMI while those in the hands-on condition would do better with the physical anticipatory steering HMI was not supported - no significant interaction effect was found.

Based on our development and design-stage testing, we believe that a key challenge for future steering wheel interfaces will be the task of separating three pieces of information: the vehicle's current state, the driver's input, and the vehicle's intended action. Whereas these three things are one and the same in manual driving, these states can diverge in shared-control autonomy. Any aliasing of these states at the steering wheel could confuse the user.

IX. Conclusions & Future work

In this paper we have described a new concept of anticipatory steering for automated vehicles that shows drivers the upcoming lateral action of the vehicle. We prototyped and tested this concept, and found that the physical anticipatory steering system was successful in allowing the driver to recognize and react faster to steering mistakes made by automation. We were unable to find a significant improvement in driver performance using the visual anticipatory steering system. Future work will investigate if longer exposure to the system would allow drivers to use it more effectively. We can also try to vary the look ahead time used by our anticipatory system by different amounts in different conditions.

This study used the scenario of having to stay on the highway and not take an exit - an automation failure requiring a fast response from the driver, but not an immediately safety-critical situation. The added risk in a safety-critical event might have an effect on driver performance, but is difficult to test in a driving simulator. In addition, different failure scenarios can be tested to confirm the viability of the system.

These study results pave the way for future work where these HMI concepts can be implemented and tested on a real autonomous driving system outside the driving simulator. On-road testing will inform us of the effectiveness of these systems in real-world conditions - the visibility of the LED strip in bright sunlight and the effect of vehicle movement and driver body biomechanics on steering control.

Outside of the automotive field, the concept of anticipatory movement can also be used with other physical controllers like joysticks if they can be actuated by the automated system. Anticipatory control interfaces might provide similar performance improvements in other real-time human-machine cooperation situations, such as teleoperation of semi-autonomous robots [21], drones and manufacturing robots.

X. Acknowledgments

The authors would like to thank Louis Tijerina from the Ford Motor company and Larry Cathey from Realtime technologies Inc. for their advice, Becky Currano for her feedback on the paper, and our colleagues Nik Martelaro and Abhijeet Agnihotri for their assistance.

References

[1] C. Katrakazas, M. Quddus, W.-H. Chen, and L. Deka, "Real-time motion planning methods for autonomous on-road driving: State-of-the-art and future research directions," *Transportation Research Part C: Emerging Technologies*, vol. 60, pp. 416–442, 2015.

[2] SAE International, "Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems," *SAE International*, vol. J3016, pp. 1–12, 2014.

[3] M. Tönnis, C. Lange, and G. Klinker, "Visual longitudinal and lateral driving assistance in the head-up display of cars," *6th IEEE and ACM International Symposium on Mixed and Augmented Reality*, 2007.

[4] B. Mok, M. Johns, N. Gowda, S. Sibi, and W. Ju, "Take the Wheel: Effects of Available Modalities on Driver Intervention," in *IEEE Intelligent Vehicles Symposium, Accepted for submission*, 2016.

[5] D. A. Norman, "The human side of automation," in *Road Vehicle Automation 2*. Springer, 2015, pp. 73–79.

[6] T. B. Sheridan, *Telerobotics, automation, and human supervisory control*. MIT press, 1992.

[7] M. Steele and R. B. Gillespie, "Shared Control Between Human and Machine: Using a Haptic Steering Wheel to Aid in Land Vehicle Guidance," *Human Factors and Ergonomics Society, 45th Annual Meeting*, vol. 45, no. 23, pp. 1671–1675, 2001.

[8] S. M. Erlien, S. Fujita, and J. C. Gerdes, "Shared Steering Control Using Safe Envelopes for Obstacle Avoidance and Vehicle Stability," *IEEE Transactions on Intelligent Transportation Systems*, 2016.

[9] S. J. Anderson, S. B. Karumanchi, K. Iagnemma, and J. M. Walker, "The intelligent copilot: A constraint-based approach to shared-adaptive control of ground vehicles," *IEEE Intelligent Transportation Systems Magazine*, vol. 5, no. 2, pp. 45–54, jan 2013.

[10] R. Chipalkatty and M. Egerstedt, "Human-in-the-loop: Terminal constraint receding horizon control with human inputs," *Proceedings - IEEE International Conference on Robotics and Automation*, 2010.

[11] R. Parasuraman and V. Riley, "Humans and Automation: Use, Misuse, Disuse, Abuse," pp. 230–253, 1997.

[12] B. D. Seppelt and J. D. Lee, "Making adaptive cruise control (ACC) limits visible," *International Journal of Human Computer Studies*, vol. 65, no. 3, pp. 192–205, 2007.

[13] J. P. Switkes, E. J. Rossetter, I. A. Coe, and J. C. Gerdes, "Handwheel Force Feedback for Lanekeeping Assistance: Combined Dynamics and Stability," *Jrnl of Dynamic Systems, Measurement, and Control*, 2006.

[14] D. a. Abbink, M. Mulder, and E. R. Boer, "Haptic shared control: Smoothly shifting control authority?" *Cognition, Technology and Work*, vol. 14, no. 1, pp. 19–28, 2012.

[15] M. Johns, B. Mok, D. M. Sirkin, N. M. Gowda, C. A. Smith, W. J. Talamonti Jr, and W. Ju, "Exploring Shared Control in Automated Driving," pp. 91–98, mar 2016.

[16] P. Kerschbaum, L. Lorenz, and K. Bengler, "Highly automated driving with a decoupled steering wheel," *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 58, no. 1, 2014.

[17] E. Bretz, "By-wire cars turn the corner," *IEEE Spectrum*, vol. 38, no. 4, pp. 68–73, 2001.

[18] M. F. Land and D. N. Lee, "Where we look when we steer." *Nature*, vol. 369, no. 6483, pp. 742–744, 1994.

[19] R. Grasso, P. Prévost, Y. P. Ivanenko, and A. Berthoz, "Eye-head coordination for the steering of locomotion in humans: An anticipatory synergy," *Neuroscience Letters*, vol. 253, no. 2, pp. 115–118, 1998.

[20] A. Balachandran, M. Brown, S. M. Erlien, and J. C. Gerdes, "Predictive Haptic Feedback for Obstacle Avoidance Based on Model Predictive Control," *IEEE Transactions on Automation Science and Engineering*, vol. 13, no. 1, pp. 26–31, 2016.

[21] L. Takayama, E. Marder-Eppstein, H. Harris, and J. M. Beer, "Assisted driving of a mobile remote presence system: System design and controlled user evaluation," in *IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2011, pp. 1883–1889.