The Effects of Driver Coupling and Automation Impedance on Emergency Steering Interventions

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Abstract—Automatic emergency steering maneuvers can be used to avoid more obstacles than emergency braking alone. While a steer-by-wire system can decouple the driver who would essentially act as a disturbance during the emergency steering maneuver, the alternative in which the steering wheel remains coupled would enable the driver to cover for automation faults and conform to regulations that require the driver to retain control authority. In this paper we present results from a driving simulator study with 48 participants in which we tested the performance of three emergency steering intervention schemes. We analyzed cases in which the driver was decoupled and the automation given full authority, or the driver was coupled and the automation given a low impedance, or the driver was coupled and the automation given a high impedance. Two types of unexpected automation faults were also simulated. Results showed that a high impedance automation system results in significantly fewer collisions during intended steering interventions but significantly higher collisions during automation faults when compared to a low impedance automation system. Moreover, decoupling the driver in emergency interventions did not seem to significantly increase the time required to hand back control to the driver. When coupled, drivers were able to cover for a faulty automation system and avoid obstacles to a certain degree, though differences by condition were significant for only one type of automation fault.

Index Terms—automatic steering intervention, intelligent transportation systems, automation impedance, human factors

I. INTRODUCTION

Progress in the development of vehicle automation and advanced driver assist systems has made driving more efficient, comfortable, and safe [1], [2]. To date, most vehicle automation is aimed at offloading certain routine tasks from the human driver in non-emergency situations [3]. Yet automation can also mitigate or avoid accidents in emergency situations, where fast reaction times and the ability to push control up to vehicle traction limits enable automation to outperform the human driver [4]–[6]. An example is emergency collision avoidance that uses automatic braking to prevent or mitigate a collision [7], [9]. Above a certain speed and below a certain time-to-collision (shorter than about two seconds), steering maneuvers can result in more successful collision avoidance than braking [4], [5], [9]. However, unlike automatic braking systems, automatic steering intervention systems are not yet available on the road [4], [8], [10]. Accordingly, development of automatic steering intervention systems has attracted significant interest in the recent past [4], [5], [8], [10], [11].

To take over control during an emergency situation, the steering wheel can be decoupled from the driver with the use of a steer-by-wire-system [4], [12]. However, decoupling the driver invokes liability issues, especially when there is a false activation of the automation system. A decoupled steering wheel during a false activation might render the driver incapable of avoiding a collision that could be prevented [4], [11]. Further, the present legal system and code of industrial practice, as well as the principles of human-centered design, dictate that a driver should always maintain some degree of control over the vehicle [2], [13], [14].

The issues with decoupling the driver are compounded during automation dropouts (when the automation system fails to detect and avoid an obstacle). The literature provides ample evidence that highly automated systems may reduce driver vigilance and situation awareness due to a lack of sufficient involvement of the driver in the driving task and lack of timely feedback of automation actions [15]–[17]. A driver who expects that they are decoupled from the steering system during emergency situations might become over-reliant on the automation and might fail to prevent a collision during automation dropouts [1]. Moreover, the time required for the driver to resume control of the vehicle may also increase, leading to additional safety issues [10].

The alternative is to keep the driver coupled and use an automation system that intervenes through a motor on the steering system. However, with a coupled steering wheel, the steering torque applied by the driver may become a disturbance to the automation. Moreover, when faced with an emergency situation, drivers tend to hold the steering wheel straight and fight any steering intervention [4], [18]. Such a driver reaction can further subvert the automation’s efforts to prevent an accident [5], [10].

Is it possible to choose a mechanical impedance for the automation that would suppress driver disturbance yet retain
a certain driver authority? Naturally, the human driver can modulate their authority through muscle action and can always attempt to overpower the automation [1], [19]. A tradeoff appears to exist between collision avoidance provided by the automation and fault tolerance provided by the driver. Setting the automation impedance high might reduce the effect of driver disturbance at the steering wheel but might also result in an ‘authoritarian’ automation system against which the driver has to compete for control (especially during automation faults when the driver should have authority) [19], [20]. High impedance automation may also risk injuring the driver’s hands, especially when acting unexpectedly [10].

A small number of studies have analyzed driving performance with high and low impedance automation systems and coupled and decoupled steering wheels. However, studies on the effect of high and low levels of automation impedance are limited to lane keeping applications [19], [20]. On the other hand, studies focused on automatic emergency steering interventions are limited to investigations of the effects of haptic and auditory warnings in driving with a decoupled steering wheel [8], [8]. Only one study on automatic emergency steering interventions compared the performance of driving with an intermittently decoupled steering wheel to driving with a coupled steering wheel [4]. However, in this study, the automation impedance in the coupled steering wheel case was set so low that the driver disturbance resulted in a collision with every obstacle placed on the test track.

In the present driving simulator study, we investigated the effect of driver coupling and automation impedance on automatic emergency steering interventions. We designed a decoupled steering scheme and two coupled steering schemes (one with low and the other with high automation impedance), and analyzed the human-automation team performance at avoiding obstacles during emergency situations and automation faults. For half of the participants, we simulated faults by making the automation inactive near an obstacle and for the other half by simulating a false automation activation. We also tested the effect of the three coupling schemes on the time needed by the driver to take back control from the automation system.

II. METHODS

A. Participants

Forty-eight participants (27 male, 21 female) participated in this study. The participants were between 20 and 30 years old (mean 23.5 years, SD = 3.6 years), had more than two years of driving experience (mean 5.9 years, SD = 3.2 years), and self-reported as having normal or corrected-to-normal vision and normal hearing. All participants provided written informed consent in accordance with a protocol approved by the University of Michigan Institutional Review Board (ID: HUM00164233). A complete experiment – including testing, training, and survey – was two hours long. Each participant was provided a financial compensation of $30 for completing the experiment.

B. Apparatus

The experimental apparatus was a custom fixed-base driving simulator featuring a motorized steering wheel (Fig. 1a). Details pertinent to the steering wheel design, automation motor, encoders, and their assembly can be found in [3]. The virtual driving environment was displayed on three 24-inch LCD widescreen monitors positioned about 140 cm from the participant. The vehicle dynamics and control and the
virtual environment were implemented in CarSim (Mechanical Simulation Corporation, Ann Arbor, MI) and Simulink (Mathworks, Natick MA) and were computed in real-time on a Dell Precision 5820 Tower Workstation computer using an Intel Xeon W-2125 Quad-Core processor. CarSim math models and Simulink code were computed at 1000 Hz and the graphical display was rendered at 50 Hz.

The virtual environment was created in CarSim VS Visualizer, and appeared as shown in Fig. [1b]. It featured a D-Class Sedan vehicle and a two-way road with various landmarks and vehicles that provided motion cues during driving. The vehicle traveled at a constant speed of 60 km/h using ‘Constant Target Speed’ control in CarSim. Neither the participant nor the automation system had any control over speed. The two-way road was 8 m wide with 4 m wide lanes and a dashed line separated traffic in two directions. The track width of the vehicle was about 2.1 m. The entire track was 6 km long and the obstacle locations and starting stations on the track were randomized as shown in Fig. [1c]. Visual notifications and warnings were provided to the participants through a virtual dashboard on the central monitor as shown in Fig. [1d]. Finally, audio alerts were provided to the participants through a speaker located on the right side of the steering wheel. The visual and audio alerts are further described in section II-E.

C. Automation System Design

We used a pure pursuit controller to develop an automation system capable of lane keeping and obstacle avoidance. A pure pursuit controller is essentially a proportional controller that generates a steering angle to reduce the path tracking error of a vehicle at a certain ‘look-ahead’ distance on the reference path [21].

We first generated a path around the track and around obstacles that served as a reference for the controller to follow and ensured lane keeping and obstacle avoidance. A look-ahead distance of 3 m was chosen for the controller. Along with the generated reference path, the pure-pursuit controller used the longitudinal and lateral coordinates of the vehicle and the heading angle generated by the CarSim vehicle model (integrated in real-time Simulink) to generate the desired steering wheel angle that would achieve path tracking. A controller commanded a torque signal to the motor proportional to the difference between the actual and desired steering wheel angle. Different proportional gains were used for low and high impedance as further described below. The difference between the commanded and actual angles was felt by the driver as torque feedback at the steering wheel and provided haptic cues for lane keeping and automation behavior.

D. Coupling Schemes

The study employed a between-subject design with one factor (coupling scheme) at three levels. The three coupling schemes between the human driver and the automation system were: Coupled Low Impedance, Coupled High Impedance, and Decoupled with Feedback. All schemes had haptic feedback during obstacle avoidance so that drivers could read and understand the automation’s intentions.

In the Decoupled with Feedback scheme, participants had no control over the vehicle trajectory (automation had full control). Participants could, however, feel the automation torque feedback on the steering wheel. The proportional gain in Decoupled with Feedback scheme was 2.1. Drivers could also move the steering wheel in Decoupled with Feedback scheme; however, the driver’s steering input was ignored and only the steering angle produced by the automation system was passed to the CarSim model to maneuver the vehicle in the virtual environment.

In the Coupled Low Impedance and Coupled High Impedance schemes, drivers could influence the vehicle trajectory by changing the steering angle. Participants could take over control by increasing their grip and imposing a torque on the steering wheel. Conversely, drivers could yield control to the automation system by relaxing their grip (reducing arm backdrive impedance) on the steering wheel. In the Coupled Low Impedance case, the proportional gain used to determine the automation torque feedback was lower and hence the haptic feedback was weaker than the Coupled High Impedance case. The proportional gain in the Coupled Low Impedance scheme was 2.1 whereas the proportional gain in the Coupled High Impedance scheme was 4.2. As a result, it was also easier to take over control and fight the automation system in the Coupled Low Impedance case than it was in the Coupled High Impedance case. Also note that since the proportional gains used in Coupled Low Impedance and Decoupled with Feedback schemes were the same, the torque feedback experienced in the two schemes was similar.

E. Experiment Procedure

The forty-eight participants recruited to the study were randomly divided into three groups (Coupled Low Impedance (CLI), Coupled High Impedance (CHI), and Decoupled with Feedback (DwF)) of 16 participants each (9 males, 7 females).

The driving task was to keep the vehicle centered in the right lane of the two-way road and avoid any obstacles that appeared in the lane. To help the driver with lane centering, a lane departure warning appeared on the virtual dashboard (Fig. [1c]) when the deviation of the vehicle from the center of the right lane exceeded 0.6 m (the lane was 4 m wide). Obstacles in the form of pedestrians, deer, or other vehicles unexpectedly entered the road from the right side of the driving lane (Fig. [1b]) and stopped at the center of the lane. Time available to avoid the obstacles was about one second. As soon as the obstacle stopped, the automation system performed an emergency steering intervention towards the left to help the driver avoid the obstacle. During the steering intervention, the lane departure warning disappeared and an ‘AUTOMATION IS ON’ notification appeared on the virtual dashboard to indicate that the automation system was active. After avoiding the obstacle, the automation system returned the vehicle back to the center of the right lane at which point a take-over-request (TOR) notification ‘TAKE OVER CONTROL’ appeared on
The eight obstacles in the first nine formal trials were all avoided by the automation which worked as intended (see Fig. 2). This resulted in a total of 128 intended automation obstacles, as shown in Fig. 2a and Fig. 2b. Half of the participants in each coupling scheme experienced idle automation in their last trial and the other half experienced adversarial automation. This resulted in a total of eight idle automation obstacles and eight adversarial automation obstacles in each group. At the end of the experiment, participants were asked to fill out a debriefing questionnaire that was used to gather participant feedback on the three automation schemes.

F. Performance Metrics and Data Analysis

There were four dependent measures in this study: (1) Obstacle Hits, (2) Peak Excursion, (3) Excursion Time, and (4) Take-over Time. The first metric, Obstacle Hits, was defined as the total number of collisions with obstacles and was analyzed separately for intended automation, idle automation, and adversarial automation. The remaining three metrics were analyzed only for the intended automation condition. Peak Excursion was measured as the absolute maximum lateral deviation of the vehicle away from the center of the right lane while avoiding the obstacle (as shown in Fig. 3). Excursion Time was defined as the time between the instant the vehicle first departed the lane to avoid the obstacle and the instant the vehicle came back to the center of the right lane. Finally, Take-over Time was the time taken by the driver to press the red button to turn the automation off after the TOR appeared for the first time on the screen.

Obstacle Hits were analyzed using binary logistic regression. All other metrics were analyzed using linear mixed models with coupling scheme as a fixed factor and subject ID as a random factor. The significance level was set at $p < 0.05$. Post-hoc Bonferroni tests were conducted to perform pairwise comparisons between the three coupling schemes.
III. Results

Differences between the three coupling schemes were apparent in the obstacle hits and excursion metrics. Fig. 4 shows the driving trajectories taken around the obstacles by all participants in each coupling scheme. The obstacles are shown by grey ellipses and any intersection of the trajectories with the ellipse denotes an obstacle hit. More intended automation obstacles were hit in the Coupled Low Impedance group than in the Coupled High Impedance and the Decoupled with Feedback groups. In contrast, fewer idle and adversarial automation obstacles were hit in the Coupled Low Impedance group, compared to the other two groups. For the intended automation obstacles, Coupled High Impedance resulted in large excursions around the obstacles whereas the Decoupled with Feedback scheme resulted in the smallest excursions.

A. Obstacle Hits

1) Intended Automation: Out of the 128 intended automation obstacles, the Decoupled with Feedback group had no obstacle collisions (Fig. 5). On the other hand, the Coupled High Impedance group had six and the Coupled Low Impedance group had 29 collisions.

Analysis on the Obstacle Hits metric indicated a main effect of coupling scheme ($F(2, 381) = 4.791, p = 0.009$). Post-hoc comparisons further revealed that the likelihood of a hit for the Coupled Low Impedance group was significantly higher than for both the Coupled High Impedance group ($p = 0.006$) and the Decoupled with Feedback group ($p < 0.001$). Moreover, likelihood of a hit in the Coupled High Impedance group was significantly higher than the Decoupled with Feedback group ($p = 0.033$).

2) Idle Automation: In the Idle Automation case, the Coupled Low Impedance group had only two hits out of eight obstacles. Six out of eight obstacles were hit in the Decoupled with Feedback scheme, while four out of eight obstacles were hit in the Coupled High Impedance group (Fig. 5). However, the effect of coupling scheme on hits was not found to be significant ($p = 0.147$).

3) Adversarial Automation: Out of eight adversarial automation obstacles, Coupled High Impedance group had seven obstacle hits and Decoupled with Feedback group had eight obstacle hits. On the other hand, Coupled Low Impedance group had only three hits (see Fig. 5). There was a significant effect of coupling scheme in the adversarial automation case ($F(2, 21) = 6.682, p = 0.006$). Post-hoc Bonferroni tests revealed that the likelihood of a hit for the Coupled Low Impedance group was significantly lower than for the Decoupled with Feedback group ($p = 0.007$) and the Coupled High Impedance group ($p = 0.035$). No significant differences were found between the Decoupled with Feedback and the Coupled High Impedance groups.

![Fig. 4: Driving trajectories around obstacles for all 48 participants, separated by coupling scheme and automation behavior.](image)

![Fig. 5: Percent obstacle hits for three types of obstacles separated by coupling scheme. Numbers on the top of the bars indicate total number of hits out of 128 obstacles for the intended automation case, and out of 8 obstacles for the idle automation and the adversarial automation cases.](image)
B. Peak Excursion

![Graph showing Peak Excursion and Excursion Time](image)

Fig. 6: (a) Mean Peak Excursion and (b) Mean Excursion Time for the three coupling schemes. Error bars are ± 1 standard error of mean.

Peak Excursion was used to gauge which coupling scheme produced the largest deviations from the center of the right lane. Peak Excursion differed significantly between the three coupling schemes ($F(2, 346) = 4.413, p = 0.013$) (see Fig. 6a). Post-hoc Bonferroni tests revealed that the Decoupled with Feedback group had a significantly lower mean Peak Excursion than both the Coupled High Impedance group (3.70 m vs. 4.12 m, $p = 0.025$) and the Coupled Low Impedance group (3.70 m vs. 4.08 m, $p = 0.029$). No other significant differences were found.

C. Excursion Time

Excursion Time indicated how much time was spent away from the lane center during obstacle avoidance. There was a main effect of coupling scheme for Excursion Time ($F(2, 346) = 4.413, p = 0.003$) (see Fig. 6b). Post-hoc Bonferroni tests showed that the Coupled High Impedance scheme had significantly lower mean Excursion Time than both the Decoupled with Feedback scheme (3.07 s vs. 3.33 s, $p = 0.005$) and the Coupled Low Impedance scheme (3.07 s vs. 3.32 s, $p = 0.01$). No other significant differences were found.

D. Take-over Time

Take-over Time was used to measure which coupling scheme encouraged faster automation-to-driver transitions. There were no significant differences between the mean Take-over Time for the three groups ($p = 0.348$).

IV. Discussion

In this driving simulator study, we compared the obstacle avoidance performance for three different automatic steering intervention schemes which differed in the amount of control authority provided to the automation system. In the Decoupled with Feedback scheme, the driver and the steering wheel were decoupled from the tires, and automation had full control over the vehicle. In the Coupled High Impedance and Coupled Low Impedance schemes, the steering wheel was coupled to the tires, and the automation system was provided high control authority or low control authority, respectively. When working properly, the automation helped the driver avoid an obstacle that appeared unexpectedly on the road (intended automation). One of two types of automation failure was simulated during the last trial: the automation would either fail to activate when an obstacle appeared (idle automation) or it would initiate a maneuver into oncoming traffic in the absence of an obstacle (adversarial automation).

The likelihood of a collision when the automation worked properly was significantly lower in the Coupled High Impedance group than in the Coupled Low Impedance group. This finding suggests that a high impedance automation system has the potential to improve safety and performance by reducing the influence of driver disturbance during emergency situations as hypothesized in [4], [5]. However, the Coupled High Impedance group still had a significantly higher likelihood of a collision than the Decoupled with Feedback group implying that allowing even a minor driver disturbance at the steering wheel imposes some risk of collision.

It is important to note, however, that a different picture emerges in the case of automation faults. Here, the likelihood of a collision did not differ significantly between the Coupled High Impedance and the Decoupled with Feedback groups. This suggests that during automation faults a high impedance automation might behave similar to an automation system in which the driver is decoupled from the tires. Especially when the automation initiated a maneuver in the absence of an obstacle (adversarial automation), participants in the Coupled High Impedance group reported that they recognized the automation failure but found it difficult to override the automation in a timely fashion to prevent the collision. This may be the result of startle and confusion on the part of the driver who, despite being aware of the option to override the automation, was not able to exert control quickly and decisively. In the presence of an obstacle, a driver is likely to monitor the automation to ensure that it takes action. This mental readiness allows for faster and effective intervention. In contrast, in the absence of an obstacle, the driver experiences a fundamental surprise, resulting in a longer response time. A longer response time in combination with larger muscular effort required to overpower a high impedance automation significantly increases the chances of a collision. On the other hand, the likelihood of a collision in the Coupled Low Impedance group was significantly lower than for the other two coupling schemes. The Coupled Low Impedance scheme enables the driver to ‘edit’ automation control inputs fairly quickly and easily when necessary. These results are consistent with the lumberjack analogy [22]: When automation worked properly, the increased degree of automation could improve performance, but in the failure conditions, higher levels of automation lead to more significantly impaired performance.

In the idle automation case, we had expected that the Decoupled with Feedback group would promote driver complacency and over-reliance on the automation’s action ([2], [15]), and would therefore result in significantly more hits than the Coupled High Impedance and Coupled Low Impedance groups. The participants in the Decoupled with Feedback group did report that they relied on automation to avoid the obstacle
and either did not react or reacted very late to the automation dropout (which is also evident from the trajectories shown in Fig. [4]). However, no statistically significant differences in the number of hits were seen between the three coupling conditions in the idle automation case.

The excursions around the obstacles also reveal some important differences in driver behavior for the three coupling schemes. Not surprisingly, the excursions were significantly larger in the coupled driving schemes, compared to the decoupled scheme. This can be attributed to the added driver input in the coupled driving schemes. Importantly, in the Coupled High Impedance scheme, a few trajectories exhibited overshoots beyond the edge of the road (see Fig. [4]). Consistent with the findings in [19] and [20], some participants in the Coupled High Impedance group reported that the transition from manual to automated driving was sudden and disconcerting, and that the automation acted too strongly and aggressively. As a result, the participants may have initially fought the automation after seeing the obstacle, relinquished control to automation which then resulted in the overshoots. The excursions in the Coupled High Impedance group were significantly shorter than in the other two groups. One possible explanation for this finding is that participants were uncomfortable with the rather powerful automation that they found difficult to override, and therefore wanted to return to the center of the right lane as soon as possible to take back control of the vehicle. Finally, we expected that participants would take longer to take back control from automation in the Decoupled with Feedback group because of being out-of-the-loop with a decoupled steering wheel during obstacle avoidance [10], [15]. However, the differences in Take-over Time between the groups were insignificant.

In summary, the results of this study highlight a trade-off in automation design: high impedance automation can significantly reduce unwarranted driver input on the steering wheel during emergency situations but may cause driver discomfort and may be too strong to override during automation faults. This result is consistent with the hypotheses and findings presented in the past [5], [10], [17], [19], [20], [22]. Contrary to expectations, decoupling the driver during emergency interventions did not significantly increase the time required for driver to resume control or the number of collisions during automation dropouts. To combine the advantages of low and high impedance automation, an adaptive impedance system could be designed that would assume a high level of authority during emergency situations in which the automation has high confidence, and low level of authority during situations in which the automation has low confidence to give override power to the human [1], [23], [24]. The design challenge for such an automation system would be to modulate automation impedance as a function of driver intention, sensor precision, and environmental complexity.

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