Comparing Coupled and Decoupled Steering Interface Designs for Emergency Obstacle Evasion

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This work was supported by Toyota Research Institute (TRI), but it solely reflects the opinions and conclusions of its authors and not TRI or any other Toyota entity.

This work involved human subjects in its research. Approval of all ethical and experimental procedures and protocols was granted by the University of Michigan Institutional Review Board under IRB Reference ID: HUM00164233.

ABSTRACT
Automatic evasive steering maneuvers can outperform human-initiated steering maneuvers in emergency situations. A steering interface that decouples the steering wheel from the tires may enhance the efficiency of automatic steering maneuvers by providing full authority to the automation system. Yet, an alternative interface in which the steering wheel remains coupled to the tires has the advantages of enabling the driver to intervene in the event of an automation failure and preventing the human factors issues associated with decoupling the driver. In this paper, we present a driving simulator study with 64 participants where we compared four steering interface design schemes in their ability to enable successful obstacle evasion in emergency scenarios. The steering wheel was either decoupled from the tires and the automation was given full authority, or the steering wheel was coupled to the tires and the automation was provided high, low or no authority. The automation was designed to avoid all obstacles, except for the last one when it failed unexpectedly. Results uncovered a design tradeoff: as the authority of an agent (driver or automation) increases, the protection against the agent’s faults (provided by the other agent) reduces. The results also show that decoupled driving reduced driver’s vigilance and mode awareness and deprived the drivers of the authority required to intervene during automation faults. Coupled driving alleviated these issues but caused driver discomfort when designed with high automation authority and resulted in a larger number of collisions during perfect automation operation when designed with low automation authority.

INDEX TERMS
Advanced driver assistance systems, human-automation interaction, human factors, intelligent transportation systems, shared control, steering systems.

I. INTRODUCTION
Control sharing between driver and automation is aimed at improving driving safety by combining the complementary skills of human drivers and vehicle automation [1], [2]. For example, sharing control can combine the speed and tirelessness of automation with the experience and adaptability of a human driver [3]. However, in emergency situations requiring fast and precise responses, control sharing may actually have a negative effect on joint system performance. Automation systems can perform evasive steering maneuvers in emergency scenarios, including scenarios in which braking alone is insufficient to avoid collisions [4], [5]. Meanwhile, human drivers may react to emergencies by executing inadequate steering maneuvers. If steering control is shared, the inadequate steering command by the human driver may reduce the efficiency of steering maneuvers undertaken by the automation [6]. Consequently, the driver may be considered a disturbance to automation during emergency scenarios and control sharing can be considered detrimental to driving safety [7]–[9].

To remove the influence of driver disturbance on automation-initiated steering maneuvers, the driver and steering wheel can be decoupled from the tires with the use of...
a steer-by-wire system [6], [10]–[12]. In decoupled driving, the driver typically has no control over the vehicle during obstacle evasion, and automation is solely responsible for avoiding the collisions [13]. While the driver can still turn the steering wheel, only the automation command is transmitted to the tires. The driver is usually also provided torque feedback corresponding to the automation action on the steering wheel, in addition to torque from tire-road interaction [6], [14]. Thus decoupled driving gives full reign to the automation system to use evasive steering to avoid collisions.

However, automation systems are not perfect. Despite technological advances, automation is still subject to false activation and dropouts [1], [15]. Decoupling the driver during a false activation invokes safety and liability issues as it deprives the driver of the control authority required to prevent an accident [6], [16]. Due to these considerations, the present legal system and code of industrial practice dictate that a driver should always maintain some degree of control over the vehicle [17]–[19].

Decoupling the driver also invokes issues that are commonly associated with performance breakdowns in human-machine systems. Decoupling the driver while providing torque feedback may mislead the driver to believe that they are in control of the vehicle. Moreover, highly automated driving systems such as decoupled driving may reduce driver vigilance and situation awareness due to a reduced involvement of the driver in the driving task [20]–[23]. In particular, drivers who become aware that they have little or no control over the vehicle may fail to intervene if automation fails to activate [19], [24]. On the other hand, drivers unaware of their level of control authority might be surprised or confused by an automation-initiated maneuver (or lack thereof) and left wondering why automation behaved in a certain way [25], [26].

One paradigm for control sharing that may circumvent issues associated with decoupling the driver is haptic shared control [27]–[30]. In haptic shared control, the driver, the automation, and the tires are all three coupled to one another through the steering wheel. The driver has access to both the tire-road interaction and the automation action through haptic feedback. Automation acts on the steering system through a motor with a finite mechanical impedance roughly matching the driver’s biomechanical impedance [2], [27]. The driver can modulate their impedance through muscle action and can attempt to overpower automation’s action whenever they desire. A coupled steering wheel therefore allows the driver to both exert control over the vehicle and extract information about the automation’s actions [28], [29].

Coupled driving can also be designed to suppress driver disturbance in emergency scenarios [30], [31]. Choosing the mechanical impedance of automation to be larger than the impedance of a typical driver will attenuate driver disturbance while still providing the driver some control over the vehicle. However, high impedance automation may cause driver discomfort, and even a reduction in driving performance, because a large driver torque might be required to overpower the automation system [9]. For example, in [30], Mars et al. showed that high impedance automation systems result in reduced lane-keeping performance and reduced driver acceptance. Likewise, Zwaan et al. in [32] found that high impedance automation can result in lower safety margins and larger conflict torques than low impedance automation. However, unlike high impedance automation, low impedance automation might be too easy to overpower and hence might not be able to suppress the driver disturbance to avoid collisions in emergency scenarios [6], [33].

A trade-off appears to exist between the control authority provided to an agent (driver or automation) and the fault protection provided by the other agent (as depicted in Fig. 1). For high impedance automation, the protection against automation faults provided by the human driver may be low because the automation system has a high relative control authority. At the same time, the protection against driver faults (or misses or inadequate responses) would be high. On the other hand, for low impedance automation, the automation has a lower relative authority and so protection against automation faults provided by the human driver would be high but protection against driver faults provided by the automation would be low. In decoupled and manual driving, only one agent—automation or driver, respectively—has the full driving authority. These cases represent the extreme ends of the spectrum on protection against faults, as shown in Fig. 1.

To understand the influence of authority allocation on driving safety, it is important to compare driving performance between coupled and decoupled steering wheel designs, and likewise to compare the performance of driver/automation teams with low and high impedance automation systems during emergency scenarios. In [6], Heesen et al. presented a comparison of team driving performance between a decoupled and a coupled steering system in emergency situations. However, in this study a very low value of automation impedance was chosen, resulting in a collision with almost every obstacle encountered during the coupled steering case. Other studies testing the performance of emergency obstacle evasion systems have primarily focused on the

![FIGURE 1. Hypothesized fault protection tradeoff. As the control authority provided to one agent (driver or automation) increases, the fault protection provided by the other agent reduces.](image-url)
influence of haptic and auditory warnings in a decoupled driving paradigm (see, for example, studies by Sieber et al. [4] and Hesse et al. [12]).

In a previously published driving simulator study [33], we compared the driving performance between coupled and decoupled evasion schemes. However, our previous study neither investigated the fault protection tradeoff nor presented a comprehensive discussion of the influence of authority allocation on driver safety and performance. The present study adds data from 16 additional participants to our previous work, and a new manual driving control scheme, and attempts to confirm the hypothesized fault protection/performance trade-off during driver and automation faults. We induce driver faults by simply simulating scenarios with time-to-collision lower than driver’s typical reaction time and induce automation faults by either making the automation system inactive near an obstacle or by making the automation system activate unjustifiably. The fault protection tradeoff enhances the theoretical framework of the study and opens a window into understanding the influence of automation authority in emergency scenarios. Relative to our previous work, we examine driving performance by analyzing not only the excursions around the obstacles, but also the steering angles applied by the drivers, automation torque trajectories, and added survey results. We accordingly expand the discussion of the results to elaborate the relative merits of decoupled and coupled steering interface designs, especially in comparison to manual driving, and suggest steps for future work.

II. METHODS

A. APPARATUS

A fixed-base driving simulator featuring a motorized steering wheel was used as the experimental apparatus (Fig. 2a). Details regarding the steering wheel setup can be found in [2]. The simulated driving environment was displayed on three 24-inch LCD widescreen monitors positioned at 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 models and Simulink code were computed at 1000 Hz and the graphical display was rendered at 50 Hz.

We created the virtual environment in CarSim VS Visualizer (Fig. 2c). The virtual environment displayed a two-way road with various landmarks and traffic. Participants drove a simulated D-Class Sedan vehicle that traveled at 60 km/h using cruise control in CarSim. The participants were not provided any control over vehicle speed. The road width was 8 m, lane width was 4 m, and vehicle track width was 2.1 m. The entire driving track was 6 km long and, as shown in Fig. 2b, the locations of obstacles and vehicle starting points on the track were randomized. Participants were provided visual warnings and notifications using a virtual dashboard (Fig. 2d) and were provided audio alerts using a speaker. We will further describe the visual and audio alerts in Section II-D3.

B. AUTOMATION SYSTEM DESIGN

The automation system used a pure pursuit controller to perform lane keeping and obstacle evasion. A pure pursuit controller generates a steering command to minimize the path tracking error at a ‘look-ahead’ distance away from the vehicle location on the reference path [34]. First, a pilot
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C. EVASION SCHEMES
We compared four steering interface designs, for their support of successful obstacle evasion by the human/automation team during emergencies. We called these four interface designs evasion schemes. The steering wheel was either (1) decoupled from the tires and automation was given full control (Decoupled with Feedback (DF)), or (2) was coupled to the tires and to an automation system designed with a high impedance (Coupled High (CH)) or (3) a low impedance (Coupled Low (CL)), or (4) was coupled to the tires and automation was given no control (Manual Driving (MD)). (The four schemes in the order of increasing driver authority are shown on the x-axis of Fig. 1.) The Coupled Low, Coupled High, and Decoupled with Feedback conditions were further sub-categorized as shared evasion schemes, since in these schemes steering control was shared between the driver and automation. All schemes included self-centering torque feedback whereas the shared evasion schemes also included haptic feedback from the automation system during obstacle evasion.

In the Manual Driving scheme, there was no automation and participants had full control over the vehicle at all times. On the other hand, in the Decoupled with Feedback scheme, participants had no control while the automation had full control over the vehicle during obstacle evasion. Participants could move the steering wheel and feel the torque feedback corresponding to automation action and tire-road interaction but their steering input was not passed to drive the simulated vehicle in CarSim. Only the automation steering command was used to maneuver the vehicle.

In the Coupled Low and Coupled High schemes, both the drivers and automation could influence the vehicle trajectory. Drivers could wrest control from automation by co-contracting their arms and increasing their muscular impedance. Conversely, drivers could relax their arms and reduce their muscular impedance to relinquish control to the automation system. The proportional gain used in the Coupled High scheme (18.46 N-m/rad) was three times the proportional gain in the Coupled Low scheme (5.96 N-m/rad), resulting in an approximately three times larger automation torque feedback in the Coupled High scheme than the Coupled Low scheme. Consequently, the automation input was considerably harder to override in the Coupled High scheme than the Coupled Low scheme. The proportional gains used in the Coupled Low and Decoupled with Feedback schemes were kept equal. The gains were kept the same to ensure that the torque feedback in the two schemes was similar, and the only major difference between the two schemes was in terms of the amount of control drivers had on the vehicle trajectory.

D. EXPERIMENT
1) PARTICIPANTS
We recruited 64 participants (36 male, 28 female) between the ages of 20 and 30 years (mean 23.5 years, SD 3.6 years). All participants were experienced drivers (mean 5.9 years, SD 3.6 years) and had normal or corrected to normal vision and hearing. Each participant completed the experiment within about 2 hours, including testing, training, and filling out the survey. A financial compensation of $30 was provided to the participants.

2) EXPERIMENTAL DESIGN
We used a between-subjects design in this study. We randomly divided the 64 participants recruited to the study into four groups (one for each evasion scheme) of 16 participants each. There were 9 males and 7 females in each group. Participants were assigned to the four groups based on their age and driving experience to ensure that the average age and driving experience of participants in the four groups were comparable. (Average age (in years) – DF: 24, CH: 25, CL: 22, and MD: 23. Average driving experience (in years) – DF: 6, CH: 7, CL: 5, and MD: 5.63.)

3) DRIVING TASK
The driving task included keeping the vehicle centered in the driving lane and avoiding any obstacles that appeared in the lane. A lane departure warning was provided to the drivers to assist them with lane centering. The lane departure warning appeared (see Fig. 2d) when the vehicle deviated more than 0.6 m from the center of the 4 m wide driving lane. The warning was provided to ensure that every participant was at the middle of the lane when an obstacle appeared. Obstacles were designed to unexpectedly enter the road from
the right and stop at the center of the driving lane (Fig. 2c). Automation helped the driver to avoid the obstacles by performing an evasive steering maneuver to the left as soon as the obstacles stopped at the center of the lane. The virtual dashboard displayed an ‘AUTOMATION IS ON’ notification during obstacle evasion to indicate that the automation system was active. After the obstacle evasion, automation brought the vehicle back to the center of the driving lane. At this point, a take-over-request (TOR) in the form of ‘TAKE OVER CONTROL’ notification appeared on the virtual dashboard. The TOR was provided to request the driver to disengage automation and resume fully manual driving. Four seconds after the first appearance of the TOR, a speaker sent monotone auditory alerts (one beep every two seconds) to remind the driver to take over. As soon as the driver pressed the red button, automation gave full control of the vehicle back to the driver and turned off the notifications and auditory alerts.

4) PROCEDURE
First, all the participants were asked to sign a written informed consent form approved by the ethics committee at the University of Michigan (ID: HUM00164233). Before the experiment, each participant was given instructions on the screen explaining the driving task. We asked the participants to use the lane departure warning and drive as close as possible to the center of the driving lane. We also asked participants to keep their hands on the steering wheel when automation performed obstacle evasion. In the shared evasion schemes, we told the participants that the obstacles would appear unexpectedly and that the automation system would help them avoid the obstacles. In the Manual driving scheme, participants were told that they were responsible for avoiding the obstacles themselves.

Next, the participants were asked to complete two training trials and nine formal testing trials. Each training trial had one obstacle while the nine formal trials had eight obstacles in total. All the trials were six-minutes long with about a minute long break between each trial. The obstacle distribution in nine formal trials was as follows: two obstacles each in two trials, one obstacle each in four trials, and no obstacles in three trials. The nine formal trials were randomized. Moreover, to prevent any learning and adaptation effects, all the trials had different surroundings (the time of day and weather), types of obstacles (pedestrians, deer, or other vehicles), and the locations of the obstacles and vehicle starting points.

For the first eight obstacles in the shared evasion schemes, the automation worked as intended; automation attempted to avoid the obstacles without human intervention (see Fig. 3a). This resulted in a total of 128 obstacle evasion maneuvers for each of the three shared evasion schemes. Likewise, a total of 128 obstacle evasion maneuvers were also performed in Manual Driving, but the maneuvers were performed by the human drivers alone (without automation assistance). The obstacles were not visible to the drivers until one second time-to-collision. Since drivers typically need at least one second to react to suddenly appearing obstacles [4], [6], the one second time-to-collision effectively induced a “driver fault”.

In the shared evasion schemes, the nine trials were followed by one additional trial. The tenth trial always involved an unexpected “automation fault”, either idle automation (automation failed to activate in the presence of an obstacle) or adversarial automation (automation initiated a maneuver into oncoming traffic in the absence of an obstacle), as shown in Fig. 3a and Fig. 3c. The time available to avoid the obstacles during automation faults was 1.5 seconds; larger than the one second available during driver faults. Half the participants in each scheme experienced idle automation while the other half experienced adversarial automation. As a result, each shared evasion scheme had a total of eight idle automation and eight adversarial automation obstacles. The tenth trial with the automation failure was skipped for the participants in the Manual driving scheme because there was no automation. In the shared evasion schemes, we also asked each participant to fill out a survey at the end of their experiment.

E. PERFORMANCE METRICS
The dependent measures used to characterize the behavior and performance of the driver-automation teams were based on the following three categories: (1) the excursions around the obstacles, (2) the steering and torque trajectories, and (3) the surveys conducted at the end of the experiments.

Three performance metrics were based on the excursions around the obstacles (see Fig. 4): (1) Obstacle Hits, defined
as the total number of collisions; (2) Peak Excursion $E^{pk}$, calculated as the absolute maximum lateral deviation of the vehicle; (3) Excursion Time $T_e$, defined as the time between the instant at which automation turned on and the instant at which driver received the take-over-request. Obstacle Hits were used to gauge which evasion scheme enabled safest maneuvers around the obstacles during driver and automation faults. $E^{pk}$ and $T_e$ were used to explore the type of excursions performed in the evasion schemes. To determine obstacle hits, an elliptical boundary was constructed around the obstacle whose intersection with the trajectory denoted a collision. The actual obstacle boundary circumscribed the obstacle, whereas the expanded obstacle boundary (used to determine collisions) was constructed to account for the dimension of the ego vehicle (as shown in Fig. 4). Note that $T_e$ could only be computed for the three shared evasion schemes because there was no automation in the Manual Driving scheme. Moreover, only the Obstacle Hits were analyzed for the idle and adversarial automation cases. The rest of the metrics were only analyzed for the intended automation case.

The following two performance metrics were based on steering and torque trajectories: (1) Peak Steering Angle $\theta_S^{pk}$, simply defined as the peak value of the steering angle applied to avoid the obstacle and (2) Peak Automation Torque $\tau_A^{pk}$, defined as the maximum absolute torque commanded to the automation motor. $\theta_S^{pk}$ was used to investigate driver’s action on the steering wheel during obstacle evasion. $\tau_A^{pk}$ depicted how strong automation torque was during obstacle evasion. As mentioned earlier, automation torque $\tau_A$ was simply computed as a product of automation impedance $K_A$ (proportional gain) and the difference between automation setpoint $\theta_A$ and steering wheel angle $\theta_S$, that is,

$$\tau_A = K_A(\theta_A - \theta_S)$$

with $K_A$ set to 18.46 N-m/rad for Coupled High and 5.96 N-m/rad for Coupled Low and Decoupled with Feedback. Note that since $\theta_A$ was almost similar for all evasive maneuvers, $\tau_A^{pk}$ primarily depended on $K_A$ and $\theta_S$. Moreover, since there was no automation in Manual Driving, $\tau_A^{pk}$ was only analyzed for the shared evasion schemes.

Finally, two performance metrics were based on the survey administered at the end of the experiment: (1) trust in automation and (2) control over the vehicle. The participants rated the four items on a five-point Likert scale (1 - Very Low, 5 - Very High). The subjective ratings were collected only for the three shared evasion schemes.

F. STATISTICAL ANALYSES

Obstacle Hits for the idle and adversarial automation cases were analyzed using mixed model binary logistic regression. The Obstacle Hits for the Manual Driving scheme and for the intended automation case in the three shared evasion schemes were analyzed using Poisson regression analysis (the data failed the assumptions for a binary logistic regression analysis due to zero hits in one evasion scheme). The survey results were analyzed using univariate analysis of variance (ANOVA) and the remaining metrics were analyzed using linear mixed models. During the analyses, the participant ID was chosen as a random factor and the evasion scheme as a fixed factor. Post-hoc pairwise comparisons between the evasion schemes were performed using Bonferroni tests. The significance level was set at $p < .05$.

III. RESULTS

A. EXCURSIONS AROUND THE OBSTACLES

Differences in driver behavior across the four evasion schemes were apparent in the vehicle trajectories. Fig. 5 shows the vehicle trajectories taken around the obstacles by the 64 participants in four evasion schemes (with 16 participants in each scheme) separated by the type of automation behavior (intended, idle, and adversarial). The trajectories for the Manual Driving scheme represent the human driver’s performance with no assistance from the automation system. We compare the trajectories in the Manual Driving scheme with the trajectories for the intended automation case in the three shared evasion schemes. The grey ellipses depict obstacles and therefore the intersections of grey ellipses with the vehicle trajectories indicate obstacle hits. Insets on the individual plots further provide a zoomed-in view of the obstacle hits. As expected, the largest number of obstacles were hit in the Manual Driving scheme (no automation) followed by the Coupled Low scheme (weak automation) in the intended automation case. On the other hand, in the idle and adversarial automation cases, a larger number of obstacles were hit in the Coupled High (strong automation) and Decoupled with Feedback (full automation) schemes. In terms of excursions around the obstacles, Manual Driving resulted in the largest excursions whereas the Decoupled with Feedback scheme resulted in the smallest excursions.
We found a main effect of evasion scheme on the likelihood of a hit \((\chi^2(2, N = 64) = 48.8, p < .001)\). Post-hoc comparisons further revealed that the likelihood of a hit for the Manual Driving scheme was significantly higher than all the other schemes \((p < .001\) for all the comparisons). Moreover, the Coupled Low scheme showed a significantly higher likelihood of a hit than the Decoupled with Feedback scheme \((p < .001)\) and the Coupled High scheme \((p = .001)\). The Coupled High and Decoupled with Feedback schemes showed no significant differences in terms of obstacle hits.

**Idle Automation:** In the Idle Automation case, we saw the maximum number of hits in the Decoupled with Feedback scheme (6 out of 8) followed by the Coupled High scheme (4 out of 8). The Coupled Low scheme resulted in the least number of hits (2 out of 8). However, we did not find a significant effect of evasion scheme on hits \((p = .147)\).

**Adversarial Automation:** In the Adversarial Automation case as well, we saw the maximum number of hits in the Decoupled with Feedback scheme (8 out of 8) followed by the Coupled High scheme (7 out of 8). The least number of hits were seen in the Coupled Low scheme (3 out of 8). We found a significant main effect of evasion scheme on the obstacle hits in the adversarial automation case \((F(2, 21) = 6.682, p = .006)\) Post-hoc Bonferroni tests showed that the Coupled Low scheme resulted in a significantly lower likelihood of a hit than both the Decoupled with Feedback scheme \((p = .007)\) and the Coupled High scheme \((p = .035)\).

1) **OBSOLECT HITS**

**Intended Automation/Manual:** A total of 128 obstacle evasion maneuvers were performed during manual driving and during the intended automation case in the shared evasion schemes. Out of these 128 obstacles, the Decoupled with Feedback scheme resulted in no obstacle collisions (Fig. 6). On the other hand, the Coupled High scheme resulted in 6, the Coupled Low scheme in 29, and the Manual Driving scheme in 76 collisions.

We found a main effect of evasion scheme on the likelihood of a hit \((\chi^2(2, N = 64) = 48.8, p < .001)\). Post-hoc comparisons further revealed that the likelihood of a hit for the Manual Driving scheme was significantly higher than all the other schemes \((p < .001\) for all the comparisons). Moreover, the Coupled Low scheme showed a significantly higher likelihood of a hit than the Decoupled with Feedback scheme \((p < .001)\) and the Coupled High scheme \((p = .001)\). The Coupled High and Decoupled with Feedback schemes showed no significant differences in terms of obstacle hits.

2) **PEAK EXCURSION** \(E^{pk}\)

We also found a significant main effect of evasion scheme on Peak Excursion \(E^{pk}\) \((F(3, 397) = 16.98, p < .001)\) (Fig. 7a). From the post-hoc tests, it was further found that the mean \(E^{pk}\) for the Manual Driving scheme was significantly higher than the Decoupled with Feedback (5.21 m vs. 3.70 m, \(p < .001)\), Coupled High (5.21 m vs. 4.12 m, \(p < .001)\) and Coupled Low (5.21 m vs. 4.09 m, \(p < .001)\) schemes.

3) **EXCURSION TIME** \(T_e\)

Excursion Time \(T_e\) differed significantly between the four evasion schemes \((F(2, 346) = 4.413, p = .003)\) (Fig. 7a). \(T_e\) was significantly lower in the Coupled High scheme when compared with the Coupled Low scheme (3.07 s vs. 3.32 s, \(p = .01)\) and the Decoupled with Feedback scheme (3.07 s vs. 3.33 s, \(p = .005)\).
FIGURE 7. Mean values of (a) Peak Excursion and (b) Excursion Time for the shared evasion schemes. Error bars indicate standard error. (** for p < .01, * for p < .05.)

FIGURE 8. Steering angle and automation torque trajectories during obstacle evasion for all participants separated by evasion scheme. All solid lines represent the mean values of the trajectories and the shaded areas represent 95% confidence intervals. The steering angle was measured using encoders and automation torque was recorded from the simulation. The trajectories were only analyzed for the intended automation case. Thus, a total of 128 trajectories (8 obstacles each for 16 participants) were analyzed.

B. STEERING AND TORQUE TRAJECTORIES

The steering angle and automation torque trajectories revealed several differences between the evasion schemes (see Fig. 8). In comparison to the three shared evasion schemes (CH, CL, and DF), the steering angle significantly lagged in the Manual Driving scheme, indicating drivers responded slower to the obstacles without automation assistance. Moreover, the steering angles in both the Decoupled with Feedback and Coupled Low schemes lagged the Coupled High scheme. The automation torque, as expected, was the highest in the Decoupled with Feedback scheme. Moreover, the peak steering angle was the lowest in the Decoupled with Feedback scheme.

1) PEAK STEERING ANGLE $\theta_{pk}^S$

Peak steering angle $\theta_{pk}^S$ differed significantly between the four evasion schemes ($F(3, 508) = 18.63$, $p < .001$). The Decoupled with Feedback scheme had significantly lower mean $\theta_{pk}^S$ than the Coupled High (41.01° vs. 84.53°, $p < .001$), Coupled Low (41.01° vs. 82.87°, $p < .001$), and Manual Driving (41.01° vs. 101.77°, $p < .001$) schemes (see Fig. 9a).

2) PEAK AUTOMATION TORQUE $\tau_{pk}^A$

The evasion scheme also had a significant effect ($F(2, 381) = 141.162$, $p < .001$) on the peak automation torque $\tau_{pk}^A$. The mean $\tau_{pk}^A$ for Decoupled with Feedback scheme was significantly higher under the Coupled High scheme than the Coupled Low scheme (9.54 N-m vs. 3.72 N-m, $p < .001$) and the Decoupled with Feedback scheme (9.54 N-m vs. 5.19 N-m, $p < .001$) (see Fig. 9a). Moreover, the mean $\tau_{pk}^A$ for Decoupled with Feedback scheme was significantly larger than the Coupled Low scheme (5.19 N-m vs. 3.72 N-m, $p < .001$).

C. SUBJECTIVE RATINGS

Participants’ self-reported ‘trust in automation’ did not differ significantly between the shared evasion schemes. On the other hand, their self-reported ‘control over the vehicle’ was highest in the Decoupled with Feedback scheme.
significantly influenced by the evasion scheme \(F(2, 45) = 5.289, p = .009\) (see Fig. 10). (Participants answered the following prompt on a five-point likert scale: Please rate how much control you had over the vehicle during obstacle avoidance. 1- Very Low, 5-Very High.) Post-hoc tests indicated that participants reported significantly higher mean control over the vehicle in the Coupled Low scheme compared to the Decoupled with Feedback scheme \((2.44 \text{ vs. } 1.44, p = .008)\).

IV. DISCUSSION

Whether higher control authority should be provided to the driver or to the automation depends on which agent can outperform the other in a particular driving scenario. In emergency obstacle evasion scenarios, automation can often outperform the driver due to its faster reaction times. However, even in emergency scenarios, the driver might still require the means to override the automation in case the automation system misses an obstacle or activates unjustifiably. This study explored the influence of automation authority in emergency scenarios by comparing the performance of four obstacle evasion schemes.

We investigated the relative merits of providing full control authority to the automation by completely decoupling the steering wheel from the road versus sharing the control authority between driver and automation by keeping the steering wheel coupled to the road. With a coupled steering wheel, we further investigated whether a high or a low automation impedance (level of authority) promoted superior driver-automation team performance. In particular, we compared the evasion schemes in their ability to provide protection against driver and automation faults. We created an initially faultless automation system which was designed to provide protection against driver faults by helping the driver avoid obstacles that appeared unexpectedly on the road. We then introduced an automation fault to test which driving scheme allowed the drivers to prevent collisions (and thereby protect against automation faults). We also analyzed performance with purely manual driving to understand the advantages of adding automation to manual driving and the capability of drivers to avoid obstacles on their own.

Adding automation to purely manual driving improved the obstacle evasion performance. When driving manually, our participants hit 59% of obstacles which was significantly higher than the 23%, 5%, and 0% collision rates obtained in the three shared evasion schemes (Coupled Low, Coupled High, and Decoupled with Feedback respectively). This indicates that while the protection against driver faults provided in manual driving was not zero, it was still lower than the protection provided in the shared evasion schemes. Moreover, the peak excursion obtained in manual driving was significantly larger than the shared evasion schemes, indicating that without automation assistance, participants performed significantly more aggressive and less efficient maneuvers around the obstacles (as also shown in Fig. 5). From the steering angle trajectories in Fig. 8, we also see that participants react relatively slower to emergencies in manual driving than in the shared evasion schemes. These results establish the baseline obstacle avoidance performance of our participants in emergency scenarios.

The results on collisions across the shared evasion schemes confirmed the hypothesized fault protection tradeoff that we presented in Fig. 1: as the authority of an agent (human or automation) increased, the fault protection (obstacle evasion) provided by the other agent was reduced. During driver faults, our participants hit significantly more obstacles when they drove alongside the automation system with low impedance. Assuming that impedance directly corresponds to authority (see [27], [30]), the low impedance automation provided lower authority to automation and higher authority to the driver. Higher driver authority reduced the automation’s ability to suppress the driver’s tendency to fight the automation-initiated maneuvers. On the other hand, when automation was provided more authority, driver disturbance was suppressed allowing safer obstacle evasion maneuvers. This observation was further supported by the 0% collision rate obtained in the decoupled driving mode where automation was provided full control authority and driver input was completely suppressed.

On the other hand, during automation faults—in particular when the automation activated unjustifiably—our participants hit significantly more obstacles when they drove alongside the automation system with higher impedance. Participants in the high impedance automation group reported that they recognized the automation failure but found it difficult to overpower the automation in time to prevent the collision (consistent with the observations in [30]–[32]). Clearly, the high impedance automation provided more authority to automation and less authority to the drivers resulting in more collisions during automation faults. For the same reason, decoupling the steering wheel resulted in 100% collision rates because the driver had no authority over the vehicle. These results corroborate the known pitfalls of using higher levels of automation in systems where automation is subject to faults. If the automation system is unreliable, giving automation more authority precludes the driver from covering for automation faults [36].

Driving alongside the automation system with high impedance also caused driver discomfort. Some participants in the high impedance automation group reported that the transitions from manual to automated driving were abrupt and disorienting because the automation system intervened with a large force. These observations were further borne out in the peak automation torque metric, which was found to be the highest for the high impedance automation case. The discomfort experienced by the participants may also have caused significantly shorter excursion times in the high impedance automation case. It is possible that the struggle for control against the automation system forced the participants to return to the lane center earlier and shorten the duration of excursions.
One of the main objectives of this study was to investigate whether it is reasonable to decouple the driver for the duration of an obstacle evasion. Clearly decoupling the driver avoided causing driver discomfort observed in the high impedance automation case and avoided collisions during driver faults observed in the low impedance automation case. However, decoupling also resulted in the highest number of collisions when automation failed as it took away the driver authority required to intervene and prevent collisions. Further, decoupled driving degraded driver vigilance which caused collisions when automation did not activate. As shown in Fig. 5, six out of eight participants in the decoupled driving scheme were not able to avoid the obstacles when automation was inactive. Decoupling also made our drivers significantly less active during obstacle evasion. Decoupled drivers exhibited significantly lower peak steering angle than the other evasion schemes, indicating that they did not apply the steering angle necessary to avoid the obstacles (consistent with [37]).

Another shortcoming of decoupled driving is the lack of system transparency and the potential for miscommunication with the driver [38], [39]. Especially in emergency interventions, where the drivers are decoupled for a short interval but are still provided torque feedback corresponding to automation action, drivers can be misled into believing that they have some control over the vehicle. This tends to reduce driver’s awareness of the driving mode (manual or automated driving) and results in “mode confusion”, which can be detrimental to the driving performance [9], [21], [38]. In the debriefing questionnaire, five out of 18 participants in the decoupled scheme reported that they had some control over the vehicle during obstacle evasion when in fact they had no control. Two participants in the decoupled scheme reported that they tried to counteract automation because they thought they could influence the vehicle trajectory.

Note that in terms of obstacle evasion, the decoupled and coupled high impedance automation schemes exhibited similar performance. Only the peak automation torque in the decoupled scheme was significantly lower than the coupled high impedance scheme, which was expected due to the lower value of automation impedance selected in the decoupled scheme. However, there were no significant differences in the collision rates obtained in the two schemes either during driver faults or automation faults. Neither of the subjective ratings collected through the survey were significantly different between the two schemes. Both schemes provided a high authority to the automation system and resulted in performance breakdowns during automation failures and human factors issues. These results indicate that until automation is fully reliable, an obstacle evasion scheme that provides high authority to automation might cause more issues than a scheme that provides low authority to automation. Decoupling the drivers may result in mode confusion and degraded driver vigilance and high impedance automation may cause driver discomfort. Such human factors issues were not observed with low impedance automation and manual driving in our study.

There were a few limitations of this study. One limitation was the absence of speed control. Our subjects reported that the lack of brakes and throttle made it difficult to avoid collisions. While in the real world drivers may prefer braking instead of steering away from the obstacles, past research has shown that at the speed and time-to-collision chosen in our experiment, steering maneuvers result in more successful obstacle evasion than braking [4], [6], [40]. Moreover, adding speed control in the study would have made it difficult to isolate the influence of a driver’s steering behavior on obstacle evasion. Another limitation of the study was lack of warnings and alerts prior to obstacle evasions. Some subjects reported that the interventions were too abrupt and startling at times and a warning could have prepared the drivers and improved the obstacle evasion performance (consistent with [4], [12]). In future experiments it would be valuable to explore the effectiveness of providing haptic, visual, and audio alerts before the obstacle evasions. Finally, the experiment presented in this paper was performed on a low fidelity fixed base driving simulator in a lab setting. A human driver’s response to emergencies on a driving simulator is likely quite different from their response in an actual vehicle where the risk is much higher. While drivers were provided financial compensation for participating in the experiments, they were not provided any reward for avoiding the obstacles which could have influenced their performance.

V. CONCLUSION AND FUTURE WORK

This driving simulator study investigated the performance of four emergency obstacle evasion schemes during driver and automation faults. The evasion schemes differed in the amount of control authority provided to the human drivers. Drivers were either provided no driving authority by decoupling their steering inputs from the tires, or a partial driving authority by keeping them coupled with a low or high automation impedance, or full driving authority by removing the automation assistance. The results revealed a tradeoff between the control authority provided to one agent (driver or automation) and the fault protection provided by the other agent. Higher driver authority reduced automation’s ability to prevent collisions during driver faults while higher automation authority reduced driver’s ability to prevent collisions during automation faults. Moreover, coupled high impedance automation resulted in driver discomfort, because the automation system intervened with a large force that was difficult to counteract. Decoupling the drivers prevented driver discomfort and reduced collisions during driver faults by taking the driver out of the loop, but caused more collisions during automation faults. Decoupled driving further reduced driver’s vigilance and mode awareness during obstacle evasions.

As long as automation remains only partially reliable, decoupled driving appears unacceptable as it deprives the drivers of the ability to intervene during automation failures. Moreover, decoupled driving may carry human factors issues that can put both the drivers and the surrounding vehicles at risk. Coupled driving may prevent these issues but may
result in collisions during driver faults if designed with a low impedance and may result in collisions during automation faults (and driver discomfort) if designed with a high impedance. Future studies could focus on designing coupled driving schemes that are safe to operate during both driver and automation faults. One potential way forward is to design an adaptive impedance automation that would combine the features of low and high impedance automation [27], [32], [41]. Such a system would assume a low impedance (or authority) in scenarios where the automation system has low confidence and where the driver wants control, and a high impedance in scenarios where the automation system has high confidence.

DISCLOSURE STATEMENT
No potential conflict of interest was reported by the authors.

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