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TITLE: Evaluating rider steering responses to an unexpected collision hazard using a motorcycle riding simulator

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ABSTRACT

Motorcycle rider steer responses to unexpected collision emergencies have not been studied experimentally. We used a motorcycle simulator with elastic steer mechanism and modified car driving model to simulate the input-output counter steering response of two-wheeled vehicles in combination with a car pop-up paradigm from driving studies to evaluate rider responses to unexpected collision hazards. We manipulated time-to-crash – either 1s or 1.5s – to probe the threshold between not enough and just enough time to respond. The median response time of 570 ms was similar to previously recorded latencies for motorcycle emergency braking responses. Although median response time and steer torque did not depend on time-to-crash (TTC), the distribution and variability of response measures were increased when TTC was shorter. Riders showed improved lateral displacement toward the road centerline by the third TTC1.5 trial and were almost 8 times more likely to produce a successful virtual swerve avoidance maneuver in TTC1.5 rather than TTC1 trials. With 1.5 seconds to respond, riders were more consistent, with net steering inputs more congruent with the maneuvering goal compared to when they had only 1 s to respond. Comparisons of 'safe' versus 'crash' outcomes show that average response times across trials and riders are not different, but the variance in timing is lower across successful trials. We have shown than it is possible to safely study rider reactions to an emergency and observe a realistic range of steer responses to a traffic conflict using a motorcycle riding simulator. The results have relevance for the design of automatic rider assistive systems, rider behavior prediction and decision logic algorithms, PTW rider modeling and targeted training interventions.

HIGHLIGHTS

- Realistic emergency steer responses can be safely explored in a simulator
- Swerving is 8x more successful when time to collision is 1.5 rather than 1 second
- Mean response time of 570 ms was independent of time to collision or practice
- With a 1.5 second time window steering is more accurate and improves with practice
- Higher steer response variability characterizes failure, not enough time to respond

KEYWORDS: Motorcycle rider, simulator, emergency maneuver, collision avoidance, steering, response time.

1. INTRODUCTION

Compared to car drivers, powered two-wheeler (PTW) riders confronted with a sudden unexpected collision hazard face critical challenges, both in terms of the control skills needed to perform an emergency avoidance maneuver, and the increased likelihood of serious injury (or death) in the event of collision. The options are to brake, swerve, or do both, but selecting and executing the appropriate response require a minimum of both *time* and *skill*. What happens if one or both of these is lacking? Indeed, in collisions between PTWs and other vehicles, riders' attempts at avoidance maneuvers are often absent or poorly executed (e.g. Haworth et al., 2003). The term 'panic' is often used in studies of rider/driver emergency responses to describe a class of control inputs in critical situations (e.g. Savino et al., 2013; Haufe et al., 2011), but few studies have tried to identify the actual psycho-physiological factors affecting performance and behavior in sudden traffic emergencies (Dilich et al., 2002).

Driver failures in emergency response can be successfully compensated by assistance systems such as autonomous emergency braking in four-wheeled vehicles (Fildes et al. 2015), and in a range of circumstances, such systems could mitigate PTW collisions (Savino et al, 2013). However, to be safely integrated into PTWs, such smart technology must be adapted for the unique dynamics of two-wheelers and the interaction between rider actions and vehicle motion. Given the effects of steer inputs on the lean angle and stability of PTWs, these actions are particularly relevant to the determination of use cases and decision logic for when and how an automated safety system should trigger. In order to design effective onboard safety systems and appropriate triggering algorithms, it is necessary, then, to understand the range and types of steering responses that riders produce, both intentionally and unintentionally, when confronted with an unexpected collision hazard. If inappropriate steer inputs are made just before or during activation of assistive technology, crash risk could be increased instead of reduced. On the other hand, if a correct steer input is initiated early enough to avoid collision, system deployment may need to be adjusted or cancelled. The open question we identify is how to observe and measure rider responses in a collision emergency in order to determine predictive relationships between rider control behavior and vehicle outcomes that can be applied to the design and development of rider simulation models, on-board safety systems and their triggering algorithms, and even connected traffic systems. Such knowledge would also assist in determining the potential or limits for training interventions.

The other important question is how to study rider responses to collision emergencies safely. Although car driver reactions in emergencies have been investigated using simulators (e.g. Schieben et al., 2014), similar literature is lacking for PTW riders, due largely to the difficulty of reproducing motorcycling dynamics with a stationary simulator. Benedetto et al. (2014) have discussed the key issues in designing motorcycle simulators having sufficient fidelity (realism of the simulation) and validity (realism of operator behavior) to study rider behavior. The levels of fidelity seen in existing motorcycle simulators range from *reduced motion* setups consisting of a static motorcycle body, with motion cued solely through a visual display, to highly complex *dynamic* simulators capable of roll, yaw and pitch in response to steer inputs and body motions (Benedetto et al., 2014). The two main characteristics of a motorcycle simulator are lean rendering and trajectory control (Benedetto et al., 2014), but the level of realism actually required for these may depend on the research question, task conditions and aspects of rider performance being investigated. While participants show a preference for the more realistic simulators (Benedetto et al., 2014), with higher realism comes increased cost, development time and considerable hardware and software engineering challenges (Stedmon et al., 2009). Such setups are very difficult to tune, require longer familiarization periods (imposing a higher cognitive load on participants), and steering mistakes continue to occur for longer into the experimental session compared to reduced motion simulators (Benedetto et al., 2014). In reality, aspects of the most complex dynamic simulators are often disabled for research (Stedmon et al., 2009; Crundall et al., 2012; Lobjois et al., 2016) for reasons undisclosed in the literature, presumably to facilitate the data collection process and/or participant adaptation to the simulator. Others have argued that when the simulation is 'good enough' the brain adds the missing expected information (Guth, 2014). Overall, the research on simulator development and validation implicates a strong argument for simplification where possible, for both practical and theoretical reasons, with highest fidelity being prioritized for the characteristics most critical and relevant to the research question.

We used a simplified motorcycle simulator to safely investigate rider steering responses to an unexpected collision hazard in a rural road setting. The simulator was previously developed and tested for user acceptability and steer input-response output in standard lateral control maneuvers (Savino et al. 2016). The current study represents the next phase of the research investigating rider steer inputs in response to a collision emergency. We hypothesized that there is a time threshold below which it is not possible for a rider to carry out an effective avoidance maneuver, given the sensory-motor processing time required for generating an organized response to a threat stimulus plus the time required for rider actions and vehicle displacement. Specifically, we hypothesized that performance differs when riders have 1 second versus 1.5 seconds to respond before an inevitable collision. We expected to see these differences in the profiles of steering control inputs. The aims of this study were twofold: to confirm that a simplified simulator can evoke realistic emergency steer responses and to investigate how time to impact – making collision inevitable versus avoidable – influences the type and organization of rider steer inputs. Such knowledge is important to the design and safe testing of onboard rider assistance systems such as motorcycle autonomous emergency braking (MAEB).

2. MATERIALS AND METHODS

2.1. Participants

A sample of 15 motorcyclists (13 male, 2 female, mean age 48 years, *SD*=13.3, range 27-71), were recruited from the Monash University Accident Research Center (MUARC) participant database (CF 2004/851) according to the following inclusion criteria: the rider held a valid motorcycle license, was currently engaging in regular riding, and had at least one year’s experience in driving on the left side of the road. The study was approved by the Monash University Human Research Ethics Committee (CF15/180-2015000084) and all participants provided informed signed consent. Rider demographic information is given in Table 1.

Partic ID	**Age** *yrs*	**Sex**	**Age at license** *yrs*	**Freq Use**	**km in past yr**	**Trial 1.0**	**Trials 2.1-2.8**	**Mean respT** *ms*	**# Safe Trials**
P0	54	M	17	5	D	1	8	520	2
P1	28	M	19	2	C	1	6	488	3
P2	47	M	24	5	C	-	8	498	3
P3	62	M	16	2	B	1	8	554	3
P4	41	M	32	2	B	1	8	663	3
P5	43	M	26	1	A	1	7	533	3
P6	64	M	18	3	D	1	6	529	1
P7*	55	M	18	3	D	1	7	588	3
P8	38	F	18	2	B	1	8	631	1
P9	27	M	18	2	B	1	8	646	3
P10*	71	M	18	3	C	1	4	510	3
P11	38	M	16	5	C	1	8	593	3
P12	54	M	18	4	D	1	4	707	0
P13	39	M	21	4	D	1	4	542	0
P14	62	F	26	4	E	1	8	806	1
Mean	***48.2***							***587***	***2.1***
SD	***13.3***							***89***	***1.2***

**Safe on Trial 1.0*

Table 1 Participant data. Trials columns specify the number of usable trials by subject. Participant identification (*Partic ID*), weekly use (*Freq use*) was rated low (1) to high (5), response time (*respT*). Km ridden in past year (yr): A) < 1,000, B) 1,000-5,000, C) 5,000-10,000, D) 10,000-15,000, E) 15,000-20,000.

2.2. Apparatus

The motorcycle simulator (Fig. 1A), developed in Savino et al. (2016a), began as the MUARC advanced driving simulator, reconfigured for motorcycle behavioral experiments (Filtness et al. 2013). The original simulator rig consisted of the body and front wheel assembly of a Honda NSR 150cc motorcycle, (engine and rear wheel removed) mounted on a static platform. Participants could realistically control the throttle and brakes. Steering control was positive as for a car (e.g. turn handlebars right to go right). To improve the simulator's fidelity in line with the current research goals, modifications and upgrades were made according to the following criteria:

1. The importance of creating a 'real enough' counter-steer input-output logic to afford measurement of valid rider steer control inputs at speeds between 60 and 100 km/h.
2. Simulation of adequate virtual vehicle behavior and motion cueing while avoiding certain known complexities in simulator design.
3. Availability of components and software.

4. Avoidance of the lengthy participant familiarization and simulator tuning required with more high fidelity simulators.

2.2.1. Motion cueing

Due to the lack of centrifugal forces in a simulator it is impossible to reproduce full lean angle. Lean is typically rendered through partial motion cueing (platform roll) or visual cueing (virtual scene tilt), or by splitting roll angle between both (Benedetto et al., 2014). In the simplified setup, lean rendering was limited to mounting the motorcycle frame on a 3 degree of freedom commercial motion base for bounce, pitch, and roll motions. A commercial audio system with bass shaker mounted under the seat simulated engine vibration for haptic speed cues. No tilting of the visual scene was implemented, so that roll was cued solely through the platform motion. A virtual reality rural driving scene displayed on three forward-surround screens provided an immersion experience (Fig. 1A). Change of heading in response to steer actions was cued visually as lateral changes in rider POV on the virtual roadway.

2.2.2. Trajectory control

The options for rendering trajectory control are positive steering (cars, motorcycles at low speeds when active balancing is necessary) or counter steering (motorcycles at self-stabilizing speeds). Integrating both for realistic dynamic transitions between low and higher speeds presents major engineering challenges and requires a fully dynamic setup and extensive sensor array to account for rider body motion in balancing actions (Benedetto et al., 2014). Researchers typically choose either one or the other steering method, depending on the research question or simulator purpose. MotorcycleSim, for example had both capabilities, but they were not integrated and researchers had to choose one or the other mode for experiments (Stedmon et al., 2009).

The priority for realism was a steering control method that could reasonably mimic the input-output response of real PTWs, while providing comparable force feedback response (increasing resistance with increasing steer torque and roll angle). Whereas more complex designs use software-controlled motion actuators to produce this force feedback (e.g. Stedmon et al., 2009), this was simulated mechanically via a pair of pre-loaded helical springs coupling the front wheel to the motion base, as shown in Fig. 1B. This produced an elastic resistance moment in response to steering inputs at the handlebar proportional to the angle of rotation around the steering axis (equivalent elastic coefficient, 3.4 Nm/deg). The force feedback could be tuned by adjusting the elastic resistance of the springs and by adjusting the steering gain in the simulation software.

2.2.3. Previous testing and validation of steer control setup

The simulator was tested in the previous study (Savino et al., 2016a) for steer input validity and user acceptability in the performance of standard lateral control maneuvers. Validations were performed in three different ways:

1. Static calibration between steer angle and steer torque.
2. Subjective evaluation of simulator fidelity.
3. Comparison of steer torque inputs recorded in the simulator with real-world values.

Because the only output signal for rider steer inputs was change in steer angle, a static calibration was performed by rotating the handlebar to a range of angles by means of a force meter gauge attached to one of the hand grips, and calculating the associated torque at each angle. This static calibration method is justified considering that inputs applied by riders are of low enough frequencies to be effectively quasi-static (error <3%) (Savino et al., 2016a). The input-output response was tuned for a relationship between steer angle and steer torque that allowed for a steer input range up to 100 Nm in either direction. For example, 20 Nm and 60 Nm produced rotation angles of 6° and 18°, respectively. Typical steer torque inputs of 20 Nm for quick lane changes have been reported in real-world riding (Cossalter & Sadauckas, 2006).

Participants gave subjective evaluations of simulator functional fidelity (i.e. how the simulator behaves in comparison with how the user expects it to behave) during constant curve following, lane change and slalom maneuvers (see Table 3). For the lane change and slalom, participants rated the simulator as reasonably realistic in terms of steering effort, counter steer control and lateral displacement resulting from steer inputs. Steering control was declared to be acceptable to very good by 11 out of 12 participants.

Steer torques applied during simulated slalom, lane change and steady state cornering maneuvers were compared to real-world values by running simulations in BikeSim® (Mechanical Simulation Corporation, MI, USA, industry standard motorcycle dynamic modeling software, based on Sharp et al., 2004). Any comparison of simulated versus real steer torque values should consider that steer inputs during real motorcycling will vary depending on the type of vehicle, ergonomics, rider size and style, tire type/condition, environmental factors (road geometry, surface, weather) and also on the variety of ways in which a given maneuver can be performed. Table 2 provides a summary of results obtained (Savino et al., 2016a) showing that steer inputs used in the simulator were consistent with real world values in terms of direction, order of magnitude and trends in the relationships between torque and speed. In addition, the shapes of the steer profiles in turning and quick lane change maneuvers were consistent with real-world observations.

Maneuver	**Objective measures: simulator compared to real motorcycle**			
	Magnitude of steer torque	**Direction, shape of steer torque input**	**Phasing steer input vs. vehicle output**	**Torque input vs. speed**
Steady state cornering	higher	consistent	consistent	consistent (positive)
Slalom	sometimes lower	consistent	consistent	-
Lane-change	lower	consistent	consistent	consistent (positive)

Table 2 Summary of results for simulator steering input-output response, Savino et al. (2016a). For slalom, torque input versus speed relationship is not assessed because speeds were variable throughout the maneuver.

2.2.4. Riding simulation and vehicle dynamics modeling

The motorcycle's motion behavior was simulated using a modified dynamical model of a passenger car. Although a commercial out-of-the box model for simulating motorcycle dynamics was previously available from BikeSim, at the time of the study it was no longer available for simulator applications because of the declared difficulties of tailoring it to customer needs. To avoid the considerable challenges of creating functional fidelity in motorcycle riding simulators compared to car simulators (see Benedetto et al., 2014 for a review), similar to Guth, (2014) and others, we implemented a car dynamical model with inverted roll angle to mimic motorcycle lean-in behaviour in curve following. The reference vehicle was a 3 Series BMW passenger car with a 3000cc diesel engine, rear-wheel drive and manual transmission (kept in 2nd gear). To produce motorcycle counter steering response, steer torque signal (rider input) was inverted and a gain was applied for conversion to steering wheel angle before feeding the signal into the car model. The inverted roll signal from the car model was fed into the platform to produce maximum roll angles of 10° in response to steer inputs. This approach significantly simplified the control modeling problem of accounting for the many dynamic forces and factors underlying PTW travel in curved trajectories (gyroscopic and centrifugal forces, steer torque inputs, steer angle, speed, rider position, lean angle, vehicle and road geometry, etc.).

With this setup, turning the handlebar counterclockwise (negative direction), produced rightward displacement towards the center line, while turning clockwise (positive direction), produced leftward displacement, towards the left road margin. Riders were coached in the use a ‘body lean strategy’ in combination with counter steer inputs (push right to go right, push left to go left). Even with minimal platform roll, the addition of the body lean was previously reported to make steering in the simulator easier (Savino et al., 2016a), and was used in the current study to optimize behavioral validity of rider control inputs. The road reference system for the simulation is shown in Fig. 1C. A complete description of the simulator setup, car control model modifications and rationales for the steering approach are provided in Savino et al. (2016a).

2.3. Test scenario and study design

The objective of the test scenario was to provoke realistic time-limited emergency steer responses to an unexpected collision hazard. The riding context was a rural 2-lane Australian highway (left travel lane). Participants followed the roadway along alternating curves and straight stretches detailed with trees, poles and other road furniture. Instructions were to obey posted speed limits and where indicated, maintain a nominal speed of 90 km/h. In the unexpected ‘car pop up’ (CPU) event, a stationary passenger car with brake lights lit would suddenly appear directly ahead in the center of the lane. This paradigm has been used in driving simulator studies of collision avoidance systems for passenger cars (for example, see Schieben et al., 2014). Participants were not informed in advance of the collision hazard. Thus, the first CPU presentation was truly unexpected. All CPU events occurred while traveling along a straight stretch of road with a posted speed of 90 km/h, free from other traffic in either lane.

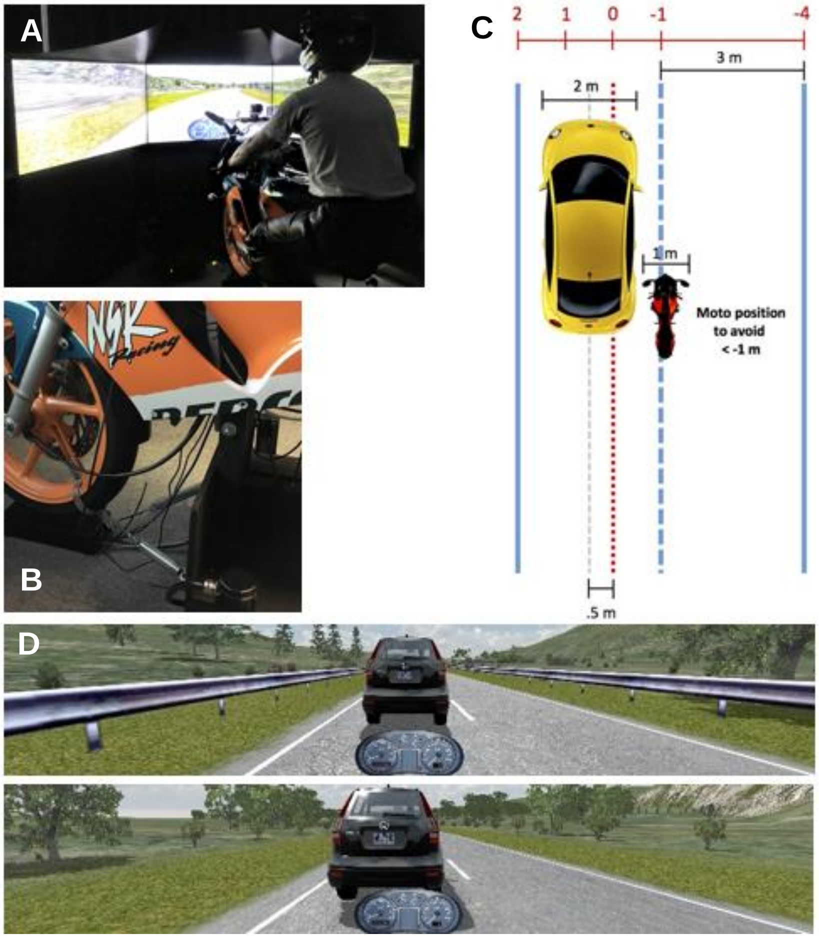

Figure 1 Experimental setup: **A)** Simulator setup, **B)** Springs coupling front wheel and motion base to simulate counter steering torque feedback to rider, **C)** Road lateral position reference scheme from the driving simulation model, **D)** two examples of the scene at the car pop-up event.

The independent variable was time-to-crash (TTC) measured from the CPU event, with two levels: 1 s and 1.5 s. TTC was also intended as a time constraint which would preclude attempts at emergency braking by making swerving the only feasible option for collision avoidance. We assumed that the limit for making an effective emergency maneuver lay between these two values based on the following justification. Given an average deceleration of -7 m/s^2 produced by experienced riders (Huertas-Leyva et el., 2019; Vavryn & Winkelbauer, 2004) and an initial speed of 90 km/h (25 m/s), necessary stopping time would be 3.6 s. Alternatively, for a speed of 25 m/s, the minimum distance from a fixed obstacle to initiate a swerve would be 18 m (Savino et al., 2012). At that distance, collision occurs in 720 ms if the rider does not react. By these calculations, a 1 s response window would allow only 280 ms after CPU to initiate a response. Consequently, 1 s should be insufficient time either to brake or swerve.

For the first trial (4-5 min. duration), TTC was 1.5 s. The following 8 trials were 90 to 120 s long, for 4 TTC1 and 4 TTC1.5 trials, randomized across participants using a Latin square design. Each trial had its own sequence of curves and straights, and different environmental scene at CPU, which occurred at a predetermined point in the track no sooner than 90 s after the start of the trial. Fig. 1D shows examples of 2 CPU scenes with and without roadside barriers. TTC conditions included two each of these variations (see Appendix). For each trial the distance between motorcycle and car at CPU time (and initial car image size and rate of change) was calculated online from motorcycle speed. Whenever a virtual collision occurred, the motorcycle was stopped with accompanying crash sound effects. Participants were given a brief pause between trials.

2.4. Protocol

Each participant performed one 2-hour experiment. After completing a questionnaire to provide demographic data and information on riding habits, the participant put on helmet and gloves and underwent a familiarization session in the simulator.

2.4.1. Familiarization

Practice trial 1: empty roadway (approx. 5 minutes). While seated on the motorcycle, the participant was given explicit coaching on basic control actions, with particular focus on the steer mechanism and strategy for lateral control of the simulator. The first trial was a roadway free from obstacles or traffic. The participant was directed to accelerate to a given speed, cruise at a constant speed, brake to a given speed, turn left by rotating the handlebar right, turn right by rotating the handlebar left. The participant then practiced riding independently, maintaining speed within a 40-80 km/h range.

Practice trial 2: rural road with traffic (approx. 10 minutes). To improve familiarity with the dynamic response of the simulated vehicle, participants were instructed to ride as they would in the real world, obeying traffic rules and signs, taking account of road and traffic conditions, and avoiding collisions. The 5 km long rural track included traffic traveling in both directions and opportunities for lane changes, overtaking and speed adjustments according to posted limits (60 and 90 km/h). After familiarization, participants completed a subjective evaluation of simulator realism and were given a few minutes to relax. Once their well-being and willingness to continue were confirmed they proceeded to the experimental trials.

2.4.2. Data collection

For experimental trials, participants were given the same objectives as for Practice trial 2: ride safely, observe rules and avoid collisions with other road users or fixed obstacles.

Trial 1.0: First unexpected collision scenario. Participants were told the trial would last 10 minutes and were given no warning of any surprise collision events. After 4-5 minutes of riding, the CPU was presented. By this time, participants had accumulated on average 18 minutes of simulated riding experience (*range*: 16-26 min, *SD* 2.85).

Trials 2.1-2.8: Successive collision scenarios. Participants were informed that the remaining trials would be shorter and that they would be similar to the first experimental trial, with no further details given. The courses also included curves, braking, oncoming traffic and the opportunity to pass a slow vehicle (for half of the trials, divided equally between TTC conditions).

2.5. Data and analysis

Data collected during the simulation included lateral lane position (m), heading angle, velocity (m/s), applied steer torque (Nm), brake pressure (0-10 normalized range), throttle angle (0-10 normalized range). Steer rate, velocity at CPU time, net lateral displacement and the second integral of steer torque (STi2) were calculated parameters. All data signals were sampled at 60 Hz.

Of the 135 intended trials (9x15 participants), 19 trials had no data. For 4 trials (participants P01, P02, P05, P06, P07), 1-2 trials were lost due to data saving problems. For participants P10, P12, P13, the researcher stopped the experiment after 4 trials, having each completed 2 of each TTC condition. Reasons for stopping were lack of good speed control/no overtaking attempted (P10), insufficient time to complete experiment (P12), or concern that the rider's over-controlling actions would lead to simulator sickness (P13).

Descriptive and statistical analyses were performed on steer response time, steer rate, steer torque, lateral lane position and displacement at specific delays relative to the CPU event. Steer response time was determined as the time, post CPU, at which applied steer torque deviated from zero, before the first main peak. To determine maximum steer rate, the difference was calculated between the first main minima or maxima in steer torque and the point at which steer torque deviated from zero or a previous opposite signed smaller peak, divided by *dt* (see Fig. 3A).

Assessment of net steer outcome (steering effectiveness) required quantification of rider steer input profiles for comparison to vehicle position outcome, even assuming not enough time for the effects of steer inputs to be fully deployed (i.e. the trial ends in a simulated collision). We calculated the second integral of steer torque (STi2) from time of CPU to CPU+1s. This parameter allowed direct comparisons between the two different TTC conditions while also taking into account the lag between steer input and trajectory change. As the integral of steer input yields heading variation, the greater the cumulative steering input, the greater the heading variation. However, if high steer torque inputs are applied in alternating directions, veering first in positive, then negative directions as in an overtaking maneuver, they could cancel each other out, for no net displacement. Thus, net change in heading might be close to zero, but the cumulative displacement would not be zero. We hypothesized that with not enough time to react, a panic response could involve 'indecisive' oscillating steer inputs, such that even a large value for single steer integral could be equated with a small final lateral displacement. By taking the second integral, we obtained the effect on displacement due to heading variation. Thus, the first integral of steer torque provides a proxy for cumulative change in heading while the second integral is a proxy for displacement. The second integral also accounts for the effect of differences in timing of steer inputs, as those applied later will have less effect on net displacement.

Data analyses were performed using custom Matlab® (The MathWorks, Inc., Natick, USA) script and the Matlab Statistics Toolbox. Because of the non-parametric nature of the data (confirmed through Kolmogorov-Smirnov tests for normality), unless otherwise stated, statistical analyses were performed using Wilcoxon rank sum and signed rank tests (for unequal/independent and equal/related sample comparisons, respectively). Tests for equal variance were performed on some parameters. Significance level was set at $p<.05$.

3. RESULTS

Figure 2 shows a comparison between the steer torque profiles and trajectory changes for two ideal real-world lane changes simulated using BikeSim (Figs. 2A & 2B) versus an overtaking maneuver (Fig. 2C) and an emergency avoidance maneuver (Fig. 2D) recorded in during Trial 1.0 for participant P07. The similarities provide additional validation of the simulator's input-output response and participant steer input behavior. Note that the overtaking maneuver occurs in a much longer time frame and with lower peak-to-peak steer torques compared to the emergency maneuver. P07 was the only participant to perform a successful avoidance maneuver on the first CPU presentation.

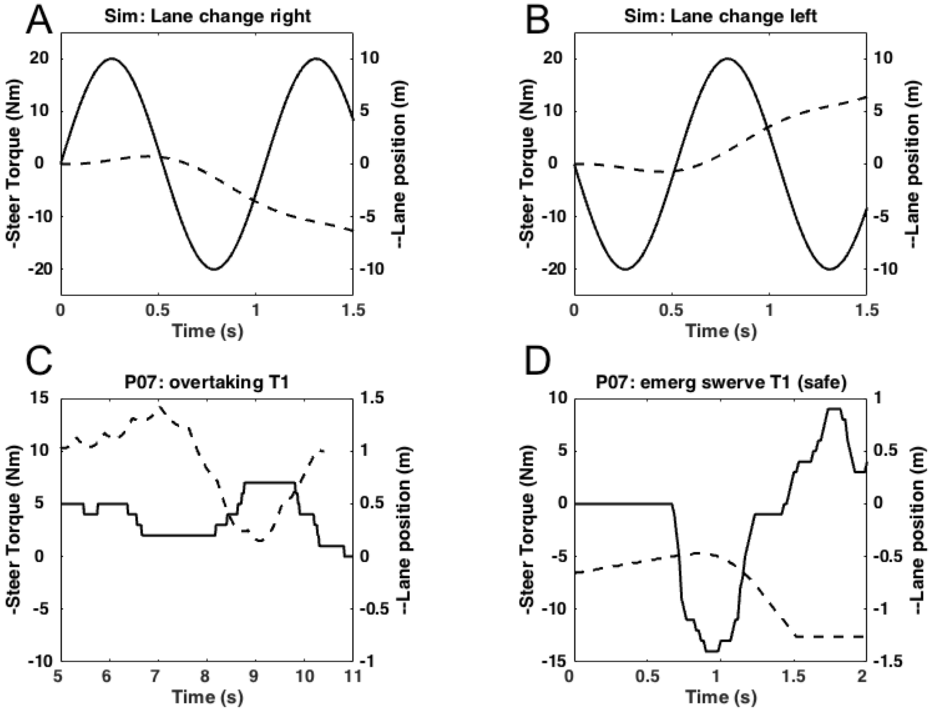

Figure 2 Comparisons of real world and simulated lateral control maneuvers. Top row left to right: lane change to the right, lane change to the left, respectively (simulated in Bikesim for a sport motorcycle at 90 km/h). Bottom row, data from participant P07, both from the first trial (T1). Solid lines are steer torque, dashed lines are trajectory (lateral position).

3.1. Subjective evaluations of simulator handling and feedback

All participants used the body lean strategy in combination with counter steer inputs, confirmed by observation and questionnaire. Although one participant declared not to have used it, observation confirmed use of body lean. Participants responded to the statements, 'Steering feedback was realistic', 'Response to steer was realistic', and 'Perception of motorcycle lateral displacement was realistic' using a 5-point Likert scale 1 = *strongly disagree*, 5 = *strongly agree*, for an overall rating of 3.1/5. Results are provided in Table 3 along with comparisons of ratings from the previous study, showing a consistency in subjective ratings of an acceptable level of realism for the simulator steer control.

Maneuver	**Subjective evaluation of simulator realism**					
	Steer torque feedback *haptic*		Steer Response *visual*		Perception of lateral displacement	
Steady state cornering	**2.7**	3.3	**3.1**	3.6	**3.4**	3.7
Lane-change	**3.1**	3.3	**3.1**	3.5		

Table 3. Participant subjective ratings of steer response and force feedback, 5-point Likert scale with maximum score=5. Bold values correspond to the current study, non-bold values are from Savino et al. (2016a).

3.2. Description of Initial conditions (at time of CPU event)

To rule out the possibility of any confounding systematic differences between TTC conditions at car pop-up time, comparisons were performed on the following parameters.

3.2.1. Initial lateral lane position

The virtual highway was 6 m wide with 2 opposing lanes (see Fig. 1C). Overall, median lateral lane position of the motorcycle at CPU time was 0.59 m right of center of the travelling lane (0.91 m left of the highway center line). There was no difference in initial lane position at CPU between TTC1 (*Mdn*= -.16 m) and TTC1.5 (*Mdn* =.04 m), *T*=464.5, *p*=0.292. Assuming the car was 1.8-2 m wide and centered in the lane, the median position puts the motorcyclist in line with the driver of the car, typical of a real-world road strategy of maintaining a safe distance from the center line while allowing a better line of site between PTW rider and oncoming traffic (view + conspicuity).

3.2.2. Velocity at CPU

Difference in velocity at CPU could constitute a confounder since this parameter is used in the driving simulation model to determine the size and rate of change of the car pop-up image. Nominal speed at CPU was set at 90 km/h. Overall, riders had a median velocity of 86.2 km/h (*SD* 6.77) at CPU. There were 5 outliers below 75 km/h. There was no difference in velocity at CPU between TTC1 (*Mdn*=86.2) and TTC1.5 (*Mdn* =86.7), *T*=403.5, *p*=0.089.

3.3. Performance indicators and response characteristics

3.3.1. Steer torque range

Minimum (rightward) and maximum (leftward) steer torques were -96 Nm and 86 Nm, respectively. These were the extremes for the TTC1 condition. For the TTC1.5 condition, minimum and maximum were -74 Nm and 83 Nm. Minimum peak-to-peak steer torque across subjects by trials was 0 Nm (no steering response) and maximum was 174 Nm.

3.3.2. Steer response time

Minimum delay between CPU and the first clear steer action (ignoring any low amplitude, transient peaks that would not influence vehicle trajectory) was 350 ms. Maximum delay was 770 ms (excluding 11 outliers ranging from 830 ms to 1.01 s). Overall, median steer response time was 570 ms (*Mean*=590 ms, *SD*=142). Fig. 3B shows the distribution of steer response times. Mean steer response times for each subject are included in Table 1.

Time-to-crash did not influence either median steer response time (TTC1: *Mdn*=530 ms, TTC1.5: *Mdn*=570 ms), *T*=420, *p*=0.197, or response time variance (TTC1: *SD*=102 ms, TTC1.5: *SD*=103 ms), *CI*=[.327 2.898], *F*(14,14)=.973, *p*=0.960. Median response time was not different for crash cases (*Mdn*=550) versus safe outcomes (*Mdn*=520), ranksum *T*=1326, *p*=0.108. However, the variance in steer response time amongst successful avoidance maneuvers (*SD*=96 ms, $SD^{2=}$9216) was less than half that of crash cases (*SD*=150 ms, $SD^{2=}$22500), *CI*=[.229 .791], *F*(29,71)=0.407, *p*=.009. These results suggest that median response time reflects a physiological limit in sensory-motor processing time, possibly in part determined by the specific task requirements and constraints (such as time), while the differences in variance in response time relates to the different probability distributions for successful versus unsuccessful performance of this task.

Overall (TTC trials pooled), there was no evidence of a decrease in response time as a result of practice (Trial 1.0: *Mdn* =720 ms; last trial: *Mdn* =580 ms), *T*=65.5, *p*=.173), nor was there a difference in response time by TTC condition between first and last trials (TTC1: *diff*= -16.7 ms, *T*=50, *p*=0.771; TTC1.5: *diff*=8.3 ms, *T*=3, *p*=1.000. Recall that the Latin square method was used to randomize trial sequence, so the final trial was not the same scene for all subjects.

A **B**

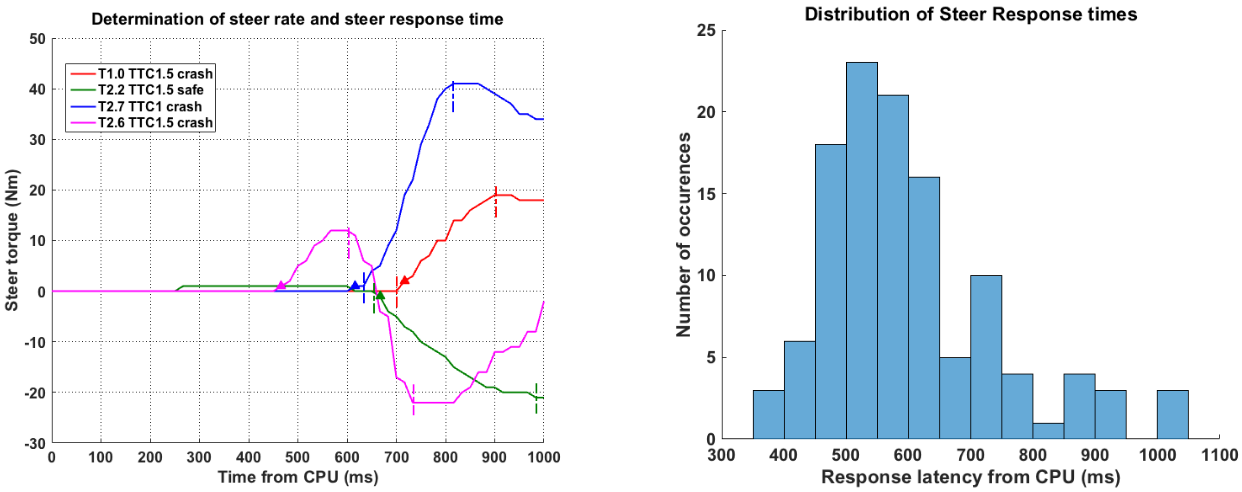

Figure 3 Steering parameters obtained from steer torque. **A)** Steer rate was calculated between last zero torque value (or change in direction, pink line) and first main peak (hatch lines) - examples from individual trials. Triangles indicate steer response times. **B)** Distribution of steer response times (TTC conditions pooled).

3.3.3. Lateral lane position as performance outcome

Fig. 4A shows lane position at the expected crash time for TTC1 (top) and TTC1.5 (bottom panel, including trial 1.0) ordered by trial sequence. For this analysis we chose to ignore the possible effects of slight braking inputs by some subjects, as justified by Kamm's Circle theory which shows that swerve trajectory remains approximately the same with or without braking (see Giovannini et al., 2013). It is clear that when the rider had only 1 s to respond, there was little deviation from the mean initial lane position of 0.9 m left of the highway center line. However, with 1.5 s to respond, final lateral positions were spread across the entire roadway. This result is not surprising, given that the PTW had an additional half second to maneuver. To account for the confounder of movement time differences, we tested lane position at CPU+1s for both conditions. Fig. 4B shows the distribution of lane positions at different time points by TTC condition (Trial 1.0 excluded). There was no difference in lane position at CPU+1s between TTC conditions (*Mdn*=.04), signed rank *T*=464.5, *p*=0.292. For plots of change in lane position for all trials by subject and TTC condition, see Fig. A2 in the Appendix.

A

B

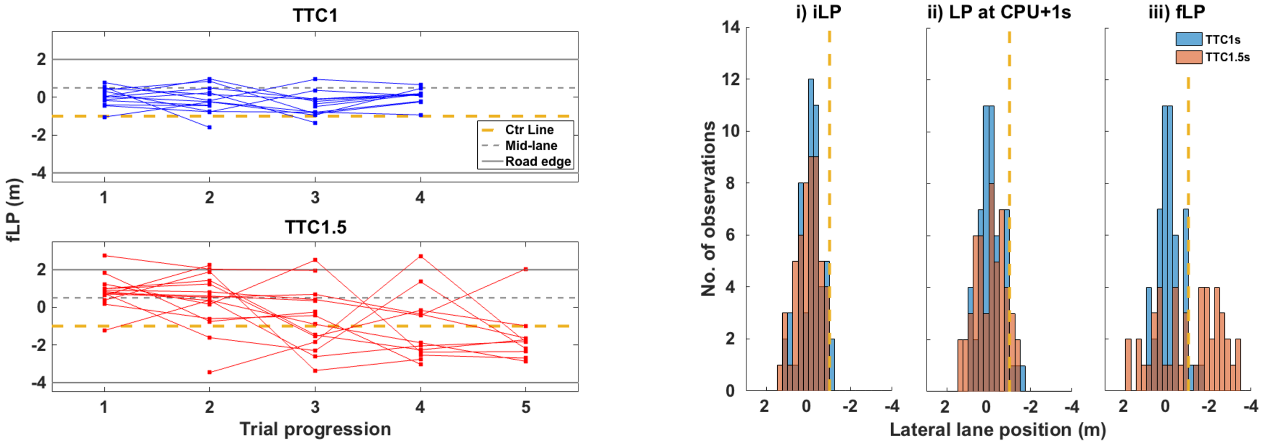

Figure 4 Lane position outcomes. **A)** Final lateral position by rider and trial sequence for the 2 TTC conditions. Lines represent single participants, squares are the data points for each trial, Trial 1.0 included. **B)** Distributions for lateral lane positions at (i) CPU, (ii) CPU+1s, (iii) CPU+TTC. Note that the plots are the same in (ii) and (iii) for the TTC1 (blue) group. Trial 1.0 excluded. Dashed yellow line denotes roadway center line.

A Kruskall-Wallis repeated measures test was performed on final lane position by trial sequence for the TTC1.5 condition only. Overall, there was a significant change in lane position outcomes, $H(4)=18.9$, $p<.001$. Post hoc tests (Wilcoxon signed rank, results in Table 4) revealed that riders were better able to produce a 1.5 m greater right lateral displacement by the third TTC1.5 trial. Thus the improvement was not merely due to having one additional trial of the TTC1.5 condition.

Comparison	*Mdn diff (m)*	*p*	Ranks
1 & 5*	-2.64	.0078	44
1 & 4*	-2.77	.0020	65
1 & 3*	-1.47	.0081	82
2 & 5	-2.38	.0176	50
2 & 4	-2.51	.1514	58

**Significance at adjusted p<.01.*

Table 4 Post hoc comparisons of final lateral lane position by trial order in TTC1.5 condition.

3.3.4. Functional assessment of final lane position: crash vs. avoidance

A functional assessment of performance was performed on lateral lane position outcomes. According to the driving simulation program, successful avoidance (absence of crash) occurred in only 16 trials (none for TTC1 condition). However, determinations were based on the host vehicle being a car of width 1.8 m, not a 1 m wide PTW. To correct for identification of false crashes, we assumed that the car was centered in the lane (car center aligned at 1.5 m left of the highway center line). We further assumed the car to be 2 m wide and the motorcycle to be 1 m wide. Thus a successful swerve to avoid collision requires that PTW final position exceeds half the car's width plus half the motorcycle's width in either direction from the center of the lane. Using the reference scheme in Fig. 1C, lane position outcomes at expected collision time were categorized as successful if they were either < -1 m (at/beyond the center line) or > 2 m (at/beyond the left road margin). For outcomes > 2 m, a further criterion was set to account for the likelihood that a leftward maneuver, even avoiding collision with the car, could be considered 'wrong' in the presence of fixed obstacles. Thus, left maneuvers resulting in lateral positions > 2 m in trial scenarios 2.1, 2.2, 2.7, 2.8 were categorized as collisions with an alternate obstacle (response error) due to the presence of a guardrail near the road margin (see Fig. 1D and the Appendix**)**. Trials 2.3, 2.4, 2.5, 2.6 had no guardrails or near fixed objects, so running off the road in these scenarios could be considered less risky than colliding with the car and were thus categorized as 'successful'. Table 5 presents the results of estimated safe outcomes (including Trial 1.0). For the scenarios in which time-to-collision was 1 s, 48 out of 51 trials ended in a crash (94%). In contrast, when the rider had an additional half second to respond, the crash frequency was 35 out of 65 trials (54%).

		TTC1	**TTC1.5**
Trials	Total # trials	60	75
	No data available	9	10
	n	***51***	65
Outcomes	Crash into car	48	35
	Crash L into barrier	0	1
	Safe swerve to R	3	24
	Safe swerve to L	0	5
	Safe - R or L	3 (6%)	29 (45%)

Table 5 Safe versus crash outcomes determined from final lane positions.

3.3.5. Second Integral of steer torque as functional net steer input

Going back to the analysis in 3.3.3. which found no difference in lane position outcome between TTC conditions at CPU+1s, it could be assumed that the shorter TTC had no effect on steer performance other than not allowing sufficient movement time to carry out the maneuver. If this assumption were true, steer torque profiles from CPU to CPU+1s should not be different, especially considering that median response time was the same and that riders initiated responses in both TTC conditions: out of the total 135 trials there were only 13 non-responses, (max steer torque before collision < 5 Nm threshold, 7 in TTC1 and 6 in TTC1.5). On the contrary, we predicted that time-to-crash affects a rider's ability to organize an effective response, which would be seen in the second integral of the steer torque (STi2), representing the net steer control input. Figure 5 shows a comparison of three trials from one participant (P06) for a clearer picture of how steer torque input and STi2 related to trial outcomes. The first panel (Fig. 5A) is from Trial 1.0 (unsuccessful), for which steer torque was low, lane position change almost nil, and STi2 was only -0.02 Nms^2. In Trial 2.1 (Fig. 5B), P06 also crashed, despite a large maximum peak steer torque in the correct direction (approx. -90 Nm), which however was not soon enough or sufficient to offset the initial steer torque in the wrong direction (first and positive peak). The third panel (Fig. 5C) represents P06's final trial and only successful swerve attempt. The shape of the steer torque profile is very similar to those of real-world lane change maneuvers (see Fig. 2A, B), as well as overtaking maneuvers recorded in the simulator (see Fig. 2C).

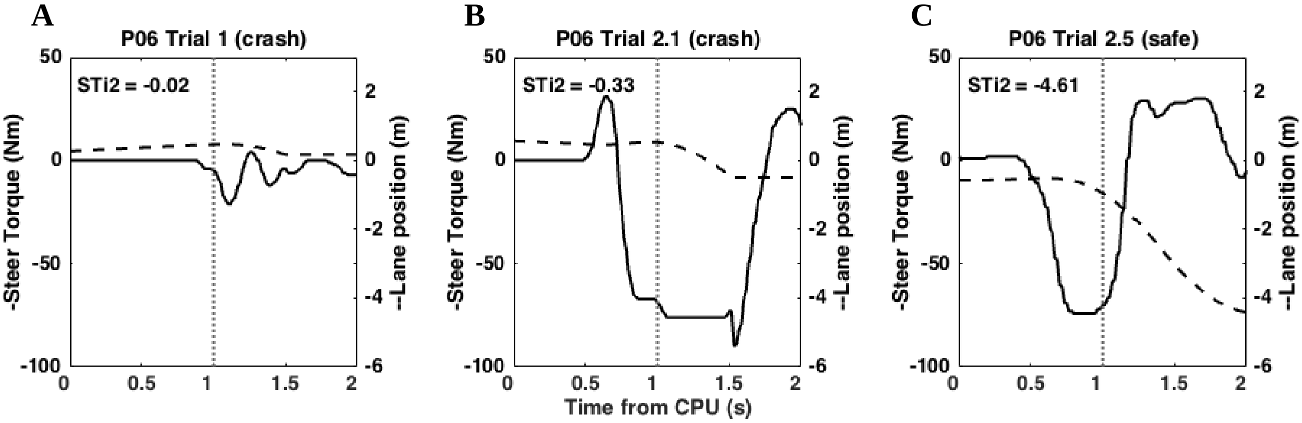

Figure 5 three trials from one participant (P06) showing different steer torque profiles and their effects on the emergency lateral maneuver. Solid lines are steer torque, dashed lines are trajectory (lateral position).

Figure 6 shows STi2 plotted against change in lane position at CPU+1s. Minimum and maximum STi2, respectively were -8.7 and 8.6 Nms^2 for TTC1, and -8.3 and 5.0 Nms^2 for TTC1.5.

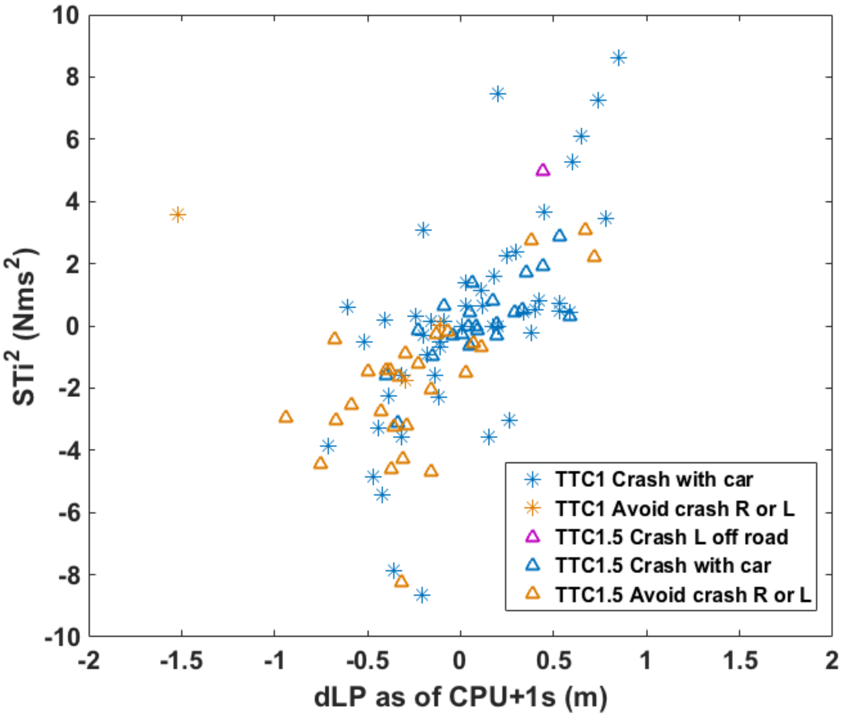

Figure 6 Second integral of steer torque (STi2) plotted against displacement by the time CPU+1s for the TTC1 (stars) and TTC1.5 (triangles) conditions. Crashes in blue and purple, safe maneuvers in gold. Negative displacement values mean counter steering towards the right (towards center line), positive values to the left (towards the road margin).

A Wilcoxon signed rank test of the possible effect of time to crash on steer inputs showed no difference in median STi2 between conditions (TTC1: *Mdn*=.161 Nms^2; TTC1.5: *Mdn*= -.483 Nms^2), *T*=721, *p*=0.097. When only crash cases were considered, there was still no difference in median STi2 between TTC conditions (TTC1 crashes: *Mdn*=0.176 Nms^2, *SD*=3.485; TTC1.5 crashes *Mdn*=0.028 Nms^2, *SD*=1.549), ranksum *T*=1739, *p*=0.881.

Although median STi2 did not differ by TTC condition, and there was no difference in lateral displacement at CPU+1s, two things are clear from Fig. 6: 1) the range of net steer inputs for TTC1 is more extreme, and 2) the weighting of leftward versus rightward steer torque is different for the two time-to-crash conditions, with TTC1.5 performance having a negative bias. A two-sample F-test for equal variances performed on STi2 confirmed an inverse relationship between TTC and the variance in net torque inputs, with that for TTC1 being twice as high as for TTC1.5 (TTC1: *SD*=3.424 Nms^2, $SD^{2=}$11.72; TTC1.5: *SD*=2.300 Nms^2, $SD^{2=}$5.29), *CI*=[1.270 3.875], *F*(50, 51)=2.216, *p*=.005. This result of greater consistency in attempting a rightward avoidance maneuver is seen when riders have more than one second to react. In contrast, TTC of 1 s is associated with a higher variability, more extreme range in steer inputs, and almost equal likelihood of applying leftward versus rightward steering inputs.

In comparing only the crash cases, variance in net steering output was 5 times higher in the TTC1 condition (TTC1: *SD*=3.485 Nms^2; *SD*$^{2=}$12.15; TTC1.5: *SD*=1.549 Nms^2, *SD*^{2}=2.40), *F*(47,23)=5.065, *CI*=[2.359 9.949], *p*<.001. This suggests that in the shorter time to react, the types of errors committed in terms of sign (spatial/directional), and the amplitude (force output) are much more random, whereas having one half second more to react may mean errors are smaller in amplitude and more spatially constrained (more coordinated).

3.3.6. Steer rate

Steer rate was also explored as a possible indicator of performance. Overall, steer rates ranged from to -883 (rightward displacement) to 615 Nm/s (leftward displacement). Overall TTC had no influence on median steer rate, (Trial 1.0 excluded) (TTC1: *Mdn*=34.0 Nm/s, TTC1.5: *Mdn*=-115.7 Nm/s), rank sum *T*=2539, *p*=0.248. However, variance in steer rate was more than 2.5 times higher for the TTC1 condition (TTC1: *SD*=331.9, *SD*^{2}=110130; TTC1.5; *SD*=202.2, *SD*^{2}=40865), *F*(47,49)=2.695, *CI*=[1.523 4.787], *p*<.001.

Furthermore, steer rates were considerably faster and biased towards rightward displacement in the safe outcomes compared to the crashes (Trial 1.0 included), (Safe: *n*=32, *Mdn*= -144.9 Nm/s; Crash: *n*=79, *Mdn*=43.6 Nm/s,), *T*=4857, *p*=0.005. Fig. 7 shows the distributions of steer rate values depending on TTC condition (Fig. 7A) or trial outcome (Fig. 7B).

A **B**

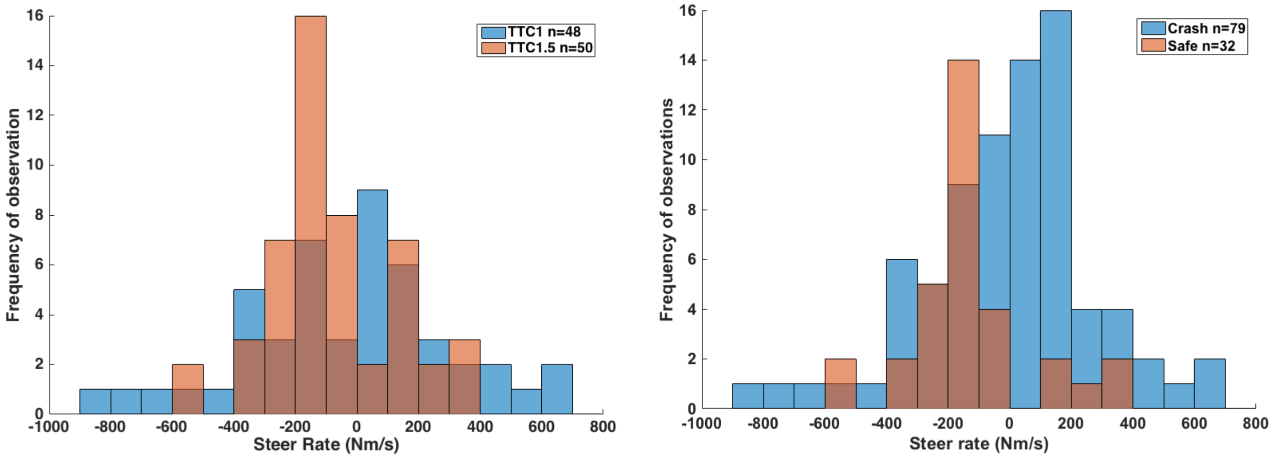

Figure 7 Frequency distributions of steer rate comparing A) TTC1 vs. TTC1.5 trials; B) Crash vs. Safe trials.

3.4. Relationship between second integral of steer torque and time-to-collision

To assess the predictive relationship between TTC and direction of steering outcomes, values for the double steer integral were categorized as either towards the left road margin (STi2 > 0) or towards the center line (STi2 < 0). A contingency table (Table 6) was created to evaluate the expected frequencies for the two categorical values, based on TTC condition.

Net steer torque (Nms^2)	Direction	TTC1	TTC1.5	Total
STi2 > 0	(L) road margin	28	16	44
STi2 < 0	(R) Ctr line	22	34	56
STi2 = 0	no displacement	1	2	3
	Total	51	52	103

Table 6 Contingency table to determine the relationship between net steer torque and time-to-collision. L=left, R=right.

A chi squared test of the contingency table revealed a significant association between time-to-collision and steer outcome (net steer torque)**,** $\chi^2(1)=5.844$, $p=0.016$. The odds ratio for the rider producing a heading change to the right instead of the left in the TTC1.5 condition was 34/16=2.1. Thus, if the null hypothesis that the time to crash was unrelated to steering direction were true, then the probability of seeing 34 out of 50 maneuvers steering rightward in this condition would be less than 2%. By contrast, the odds ratio for heading right in the TTC1 condition was 22/28=0.79. Thus in the TTC1.5 condition, riders were twice as likely to produce a net steer torque to the right, whereas in the TTC1 condition, riders showed a slightly greater tendency to the left rather than the right.

4. DISCUSSION

We investigated the steering inputs produced by a sample of experienced motorcyclists when confronted with the unexpected threat of an imminent collision. The experimental setup involved a virtual rural Australian driving scene and a simple simulator rig based on a real motorcycle, using an elastic steer mechanism integrated with an inverted car model to simulate the input-output counter steering response of two-wheeled vehicles. Two hypotheses were investigated using the car-pop-up paradigm for studying collision emergencies: 1) that performance differs when time to impact is 1 second (inevitable) versus 1.5 seconds (avoidable), and 2) that a simplified simulator setup can produce realistic emergency steer responses in riders. Steering profiles were analyzed to assess the realism of the responses evoked and to evaluate the influence of time to collision on riders' ability to produce an organized, effective evasive maneuver. This was the first study to investigate motorcyclists' responses in a simulated collision avoidance paradigm using inevitable and high-risk unexpected crash scenarios.

4.1. Rider responses to a collision hazard

The two response time windows – 1 s and 1.5 s – were chosen to explore the threshold between not enough and just enough time to produce a successful maneuver. We confirmed that with 1 s to collision, avoidance, although possible, was very unlikely (6% success), but with just half a second more, the probability of executing an effective maneuver increased to 45%. The greater final displacement seen in the TTC1.5 condition was to be expected, considering the additional half second of maneuvering time. Our results further confirmed that rider steer responses differ above and below a minimum threshold for time-to-collision. The effect of TTC on performance was seen as higher variability in the range and direction rider steer inputs. Additionally we saw a trend of increasing right lateral displacement with practice when time to crash was 1.5 s.

The functional net steer input, represented by the second interval of steer torque (STi2), was not influenced by TTC. However, the variance in net steer torque (STi2) responses was twice as high for TTC of 1 second, and when we compared only crash cases, variance was 5 times higher for TTC1 crashes compared to TTC1.5 crashes. Looking at Figure 6 we see this difference in variance as follows: in the TTC1.5 condition crashes were associated with low net steer inputs (-2 to 2 Nms^2), effectively a null response, whereas in the TTC1 condition the range of inputs was extreme (-9 to 9 Nms^2) effectively, doing much with little useful result.

In a categorical analysis of steer input direction, our hypothesis was further confirmed with the finding that riders were twice as likely to counter steer right (producing rightward displacement) instead of left in the TTC1.5 condition. In contrast, with only 1 s to respond, the likelihood that net steer torques were to the right or left was about equal. Steer rate was not affected by TTC, whereas steer rate variance was 2.5 times higher for TTC1 compared to TTC1.5 condition. In addition, steer rates for safe maneuvers were 4 times faster and biased towards rightward vehicle displacement. Steer response time was not influenced by TTC, and neither was the variance. However, response time variance for crash cases was more than twice as high as for safe cases.

4.2. Realism of evoked responses: comparisons with previous findings

4.2.1. Response times

The median steer response time was 570 ms, irrespective of time-to-crash. The range for successful maneuvers was 370-770 ms, with 370 ms also being the minimum for the TTC1.5 condition. The range for unsuccessful maneuvers was broader: 350-1000 ms, with 350 ms being the minimum for the TTC1 condition. In the TTC1 condition, only 3 out of 51 trials were successful. For these, the steer response times were 430, 520, and 450 ms, respectively. These values are larger than the maximum possible delay of 280 m**s** calculated by Savino et al. (2012). However, in that scenario the motorcycle was assumed to be aligned with the center of an obstacle 2 m wide. For a position closer to the lateral border of the car ahead as observed in this study, a smaller lateral displacement and less time would be required for execution, so a successful response could in fact occur later.

The steering response latency observed here is similar to the 680 m**s** mean latency recorded by Davoodi et al. (2012) for initiating braking in response to an *expected* stimulus in real-world motorcycling from a speed of 60 km/h. The range of response times was broader in the Davoodi study compared to the present simulator study: 190 ms to 1.37 s. In a second experiment, Davoodi et al. (2012) presented riders with an *unexpected* obstacle to provoke a truer emergency response. Mean response time was even later: 1.29 **s**, ranging from 550 ms to 2.55 s. In their test scenarios, braking response times were measured from stimulus presentation to the onset of the brake light determined offline from video. The experimenters apparently did not control for time-to-crash from when the unexpected stimulus was presented.

The higher mean latency and broader range of response times obtained in Davoodi et al. (2012) compared to the present study may be due to the following possibilities: more distractors and higher cognitive load in the real-world context and greater variability in natural tasks, greater error in the determination of time from video, a systematic delay between initiation of braking and light activation due to the time required for the brake lever to move through a certain angle before the electrical signal is engaged. Furthermore, we used median values instead of means, as the data were non-normal. The median value is less sensitive to extreme outliers which we propose may represent responses that are categorically different from those clustered around the median – for example, anticipatory or non-responses.

Thom et al. (1985) recorded shorter latencies between stimulus and brake activation in a study conducted on stationary motorcycles to measure pure response time. Mean response times for experienced versus inexperienced riders were 400 s and 440 s respectively. In a similar protocol, Davoodi et al. (2011) also obtained a mean response time of 440 s. The authors suggest that the more controlled stationary experiments probably produce shorter response times than the field tests because of the added environmental and task complexity of the latter.

4.2.2. Steer torque inputs

Caution must be taken in generalizing results obtained in a simulator to real-world scenarios. The primary concern is that the simulator characteristics - the input-output response of vehicle handling and the lack of real dynamics (acceleration, gyroscopic and centrifugal forces) renders the experience too dissimilar from reality to produce functionally valid responses in the rider. An understanding of vehicle response dynamics may shed light on the criticality of simulator dynamical fidelity vis-a-vis possible effects on rider time-limited responses to an unexpected event. Transfer functions derived from tests on real motorcycles during slalom maneuvers at around 80 km/h yield delays of around 350 ms between riders' steer inputs and roll initiation (Biral et al., 2003). Cossalter & Sadauckas (2006) obtained a similar lag of approximately 200 ms for lane change maneuvers. These vehicle response latencies suggest that on real motorcycles, the initial part of a rider's emergency steer response is likely under open loop control, since 250 ms or so must elapse before receiving any new information on vehicle motion change. Given a response time of 570 ms, the minimum latency for input-generated feedback is approximately 820 ms post-CPU. Thus we can assume that for an interval of at least the first second following the car pop-up stimulus, the accuracy of the simulator's dynamic response and the fidelity of related motion cues will not influence rider actions (reflex or voluntary) and so is not so critical during this phase. On the other hand, the functional validity of the simulator is more critical during the normal riding tasks, when movements are under sensory feedback control.

As additional evidence of the internal and external validity of the steering setup, in the sample video provided, we can observe how well participants were able to perform naturalistic riding tasks in the simulator after just 15 minutes of familiarization. During trials, participants spontaneously and consistently performed speed adjustments, lane changes and overtaking maneuvers in response to the appearance of vehicles slowing or pulling out into the lane ahead, with 2 seconds or more of advance sighting (e.g. car came into view while rider rounded a curve). In the emergency scenarios of the present study, we recorded peak-to-peak steer torque ranges as low as 0 Nm (no response) and as high as 174 Nm (participant 10, Trial 2.8), both extremes being coherent with elicitation of a 'panic' response. Incidentally, the case of the 174 Nm peak-to-peak range did not produce a successful outcome, even though STi2 was near the maximum of 7.3 Nms^2. For the overtaking maneuvers performed during CPU trials, minimum and maximum peak-to-peak steer torque was 17 Nm and 45 Nm, respectively. These results are consistent with those found in the previous study: for quick lane change maneuvers at 80 km/h in the same simulator setup, with the virtual maneuver space demarcated by traffic cones, mean peak-to-peak steer torque was 35.7 Nm (*SD*=13.3), with a range of 16.9 to 57.4 Nm (Savino et al., 2016a). Real-world values obtained using BikeSim showed a very similar average steer torque of 35 Nm (*SD*=7.0) across three different styles of motorcycle (sports, touring, and cruiser) performing quick lane changes (Savino et al., 2016a). The lower steer torque values observed for lane changes and overtaking maneuvers compared to CPU responses are congruent with slower (non-emergency) maneuvers.

Further evidence of the reliability of the simulator was seen in the similarities between the participants' subjective assessments in the two studies (Table 3). The slightly higher ratings given in the previous study are probably due to the different timing in administering the evaluation forms. In the current study, participants completed them right after familiarization, whereas in the previous study, they were completed at the end of the experiment. Considering all the above points taken together, we are confident that the steer inputs measured during the emergency maneuvers provide a good representation of real-life rider inputs in response to the sudden appearance of a collision hazard, and that the simplified simulator provides an acceptable level of fidelity for the present research questions.

5. LIMITATIONS

The steer response times observed may represent idealized (lower) values compared to real-world responses given the controlled context, limited motion and the possible effects of repetition and anticipation. We could expect response times in real collision situations to be longer since there would be more environmental and intrinsic sensory information to process and higher attentional demands.

The practice effect seen across TTC1.5 trials as an improvement in right lateral displacement may simply reflect adaptation to the simulator's input-output characteristics rather than the improvement of emergency response through practice. In the absence of retention and transfer of learning tests to real-world riding, this result does not provide evidence in support of using the test scenario as a training tool for collision avoidance. However, the result supports the claim of the functional validity of the simulator, since it shows that participants were able to adapt reasonably quickly to the input-output response, minimizing the additional cognitive load imposed by controlling a simulator, and thus improving the external validity of the responses observed.

The sudden appearance of the car on the virtual roadway may have been unrealistic, but the perceived distance of the car and rate of change of its size were congruent with the speed of the virtual motorcycle. The aim of the study was to observe steer input response times and patterns, thus using the CPU stimulus avoids the confounder of differences across riders in hazard perception skills. The truly unexpected nature of the stimulus presentation, especially in the first trial, allowed us to probe the limits of rider reaction times and explore how time to crash influences organization of an emergency lateral avoidance maneuver on a PTW.

The real-world contexts for which the present results would be most applicable would be for travel at 90 km/h along a 2-lane rural roadway, in daytime and normal weather conditions, with no other traffic at the time of the emergency event, and specifically in situations where another vehicle or obstacle is suddenly revealed, as in coming around a bend or over a hill, or when car following and the vehicle ahead suddenly slows. We would expect similar responses of opposite sign in right lane driving contexts. Studies using the same paradigm but with oncoming traffic at the time of CPU, or a more dynamic simulator, may provide further insights. It should be noted that response time, as it was defined here, was only with reference to steer inputs. Brake activation and throttle angle were also recorded but were not analyzed in this study.

Finally, steer torque was not a direct measurement but was estimated from steer angle using static calibration measurements. However, we would expect to obtain similar values to the same calibrations on a regular motorcycle with steering locked, and using strain gauges to measure force exerted on the handlebars. In other words, the resistance in a real motorcycle steering setup to a rider's applied force would be comparable.

6. CONCLUSIONS

Overall, the results provide evidence that a 1s TTC evokes confused and/or random responses. With 1.5 seconds to respond before a potential collision, riders were able to be more consistent, producing net steering inputs that are more congruent with the maneuvering goal than when they had only 1 s to respond. In addition, they got better at steering faster to move the vehicle to the right. Steer torque profiles provide evidence that even with a shorter time-to-crash, responses are initiated, and are even at the same latencies as for the 1.5s time-to-crash, however, these tend to be more random and disordered, and inappropriately graded (too little or too much force output). These results suggest that when available time to respond is too short, failure is not explainable simply by lack of enough time to complete the emergency maneuver, but that perceived lack of time contributes to failures in sensory-motor processing. It appears that the selection and programming of the human motor response is compromised, due to the intensity of the hazard stimulus, such that the generated movements are more random and less effectual. It is an open question as to what degree such movements may critically affect vehicle stability or interfere during deployment of automatic assistive systems, especially in light of the extreme values characteristic of the 1 s time-to-collision. This is an important finding and should be studied further because this is exactly the time window in which last resort assistance systems are likely to be designed to respond (Savino et al., 2016b).

Motorcycle rider steering responses to a collision emergency can be safely explored in a simplified simulator setup, allowing observation of realistic performance. Parameters found to be useful are steer rate, steer response time and the second integral of steer torque. The results presented can be applied to the 1) design of active safety systems that are aligned with human sensory-motor limitations and capabilities, 2) development of targeted, effective training tools, 3) control logic of autonomous vehicles that interact in traffic with PTWs, 4) development of realistic PTW rider control models for simulations. This is the first motorcycle study to provide insights into the so-called 'panic response' in steer control, specifically highlighting which mechanisms in the voluntary response to a danger stimulus are affected.

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APPENDIX

Figure A1 The driving contexts at CPU for each trial.

Pre-impact:

TTC = 1.5 s

1.0

2.1

2.2

TTC = 1.0 s

2.3

2.4

2.5

2.6

2.7

2.8

Figure A2 Change in lane position by rider, trial (individual arrows), and TTC condition. Sequence of trials is depicted by shading of arrows from darkest (earliest) to lightest (later). Arrow lengths are unitary, thus longitudinal distance traveled is not represented. Data for each subject is given in a pair of plots, one for TTC 1s (left) and one for TTC 1.5s (right).