



Delft University of Technology

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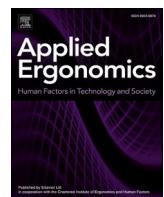
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## Emergency braking at intersections: A motion-base motorcycle simulator study

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### ABSTRACT

Powered two-wheeler riders are frequently involved in crashes at intersections because an approaching car driver fails to give right of way. This simulator study aimed to investigate how riders perform an emergency braking maneuver in response to an oncoming car and, second, whether longitudinal motion cues provided by a motion platform influence riders' braking performance. Twelve riders approached a four-way intersection at the same time as an oncoming car. We manipulated the car's direction of travel, speed profile, and its indicator light. The results showed that the more dangerous the situation (safe, near-miss, impending-crash), the more likely riders were to initiate braking. Although riders braked in the majority of trials when the car crossed their path, they were often unsuccessful in avoiding a collision with the car. No statistically significant differences were found in riders' initiation of braking and braking style between the motion and no-motion simulator configurations.

### 1. Introduction

Because of their ability to maneuver on congested roads, powered two-wheelers (PTWs) are an efficient mode of transport, especially in dense urban areas. Accident analyses have shown that a common type of collision involving a PTW in an urban environment is a situation where a car drives into the path of the PTW rider at an intersection (Clarke et al., 2007; MAIDS, 2009). Although it is the car driver who violates the formal rules (Pai, 2011), the PTW rider may have been able to prevent the crash by performing an appropriate evasive maneuver. As pointed out by Crundall et al. (2013), the majority of studies on these right-of-way crashes have been concerned with the behavior of car drivers, and little empirical evidence exists concerning the behavior of riders.

An in-depth study of human errors in PTW-car crashes showed that riders often fail to perceive and anticipate the car driver's intentions and also fail to perform a satisfactory braking maneuver (Penumaka et al., 2014). Various photo- or video-based studies have been performed to study road users' ability to predict the intentions of car drivers,

motorcyclists, and cyclists (e.g., Drury and Pietraszewski, 1979; Lee and Sheppard, 2016; Walker, 2005; Walker and Brosnan, 2007; Westerhuis and De Waard, 2017). For example, Lee and Sheppard (2016) found that participants were more accurate in judging turning maneuvers when a vehicle was indicating the turn compared to a condition when the vehicle's indicator was off. Furthermore, it was found that participants viewing video clips were able to judge whether the vehicle would turn even when an invalid turn signal was provided.

Previous studies on PTW rider's braking performance have relied on test-track experiments in which riders had to brake in response to discrete or artificial stimuli such as lights, road markings, or barricades (e.g., Davoodi and Hamid, 2013; Davoodi et al., 2012; Ecker et al., 2001a; Ecker et al., 2001b; Vavry and Winkelbauer, 2004). These studies showed that the average braking distance to an unexpected object (i.e., a barricade) when traveling at a speed of 60 km/h was approximately 52 m (Davoodi and Hamid, 2013), and that response times ranged between 0.55 and 2.55 s (Davoodi et al., 2012). Similarly, a literature review about car driver's brake response times showed that the majority of studies used simple acoustic or visual stimuli rather than

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more naturally evolving traffic situations (Green, 2000).

Several researchers have experimentally evaluated how riders respond to right-of-way violations of car drivers. Huertas-Leyva et al. (2017) investigated riders' braking behavior in response to an approaching car at a mock three-way intersection. The results showed large individual differences in mean deceleration during emergency braking (between  $3.5 \text{ m/s}^2$  and  $7.6 \text{ m/s}^2$ ), and an effect of the car's turn indicator, where deceleration values were lower when the indicator was on compared to when it was off, possibly because braking started earlier. Crundall et al. (2013) used a motorcycle simulator in a no-motion configuration to investigate how riders of different experience levels approached a three-way intersection when a car pulled out from a side road. The riders who had participated in an advanced riding training showed safer performance in terms of anticipatory slowing down before the intersection compared to regular and novice riders.

Simulators have proved to be a valuable instrument for measuring hazard anticipation skills in ethically challenging emergency events (Underwood et al., 2011). However, achieving realistic braking performance in simulators remains a challenge (Boer et al., 2001; Boer et al., 2000; Jamson and Smith, 2003). Furthermore, it is technologically challenging to implement independently working front and rear brakes on PTW simulators (Stedmon et al., 2009) as well as to simulate realistic motorcycle behavior at low speeds at which the motorcycle is unstable. Despite these technological challenges, simulators are attractive tools for studying rider behavior, as simulators offer the possibility of exposing participants to critical situations without physically at risk (Carsten and Jamson, 2011; De Winter et al., 2012).

The purpose of this study was twofold: (1) to understand how PTW riders brake at an intersection when encountering a car that might violate the formal right-of-way traffic rule, and (2) to compare how no-motion and motion configurations of the simulator affect rider's braking performance. This study addressed the following two research question:

- (1) How do riders brake in impending-crash, near-miss, and safe intersection situations?

A rider can use the car's speed, distance to the intersection, and additional cues such as the car's indicator and car's heading to anticipate the intention of the car driver (Lee and Sheppard, 2016; Wilde, 1976). In line with Huertas-Leyva et al. (2017) and Lee and Sheppard (2016), we expected that the turn indicator light would contribute to earlier braking as compared to when the car does not use its indicator light. Further, we expected that PTW riders would initiate braking earlier when the car is approaching from the right because this car can be seen to be on a collision course with the rider. If the car is approaching an intersection from the opposite direction, the PTW rider would typically not brake unless the car initiates a left turn and starts to cross the rider's path.

- (2) Do longitudinal motion cues provided by a motion platform influence riders' braking performance?

We expected that there would be no significant differences in the timing of emergency braking action between no-motion and motion because no motion cues are provided to the rider when riding straight at a constant speed in the motion configuration. Based on previous research in driving simulators (e.g., Siegler et al., 2001), we expected that riders would adopt a lower deceleration (i.e., less braking) in the motion configuration than in the no-motion configuration.

## 2. Method

### 2.1. Participants

Nine motorcycle riders (license A) and four moped riders (license AM) were recruited from the employees of Siemens PLM Software,

Belgium. One motorcycle rider withdrew from the experiment during the practice session due to simulator sickness. Three other participants partially completed the experiment due to simulator sickness (see Section 3).

The mean age of the remaining 12 participants (10 males, 2 females) was 32.9 years ( $SD = 6.1$ ). Participants had held their PTW license on average for 10.9 years ( $SD = 5.8$ ) and their driving license on average for 13.1 years ( $SD = 5.6$ ), see Table 1 for an overview of participants' riding experience. The study was approved by the TU Delft Ethics Committee (Ethics application no. 176, 2017).

### 2.2. Apparatus

#### 2.2.1. MOTORIST riding simulator

The experiment was conducted on the 'MOTORIST' motion-base riding simulator. The simulator consisted of a motorcycle mock-up, type Piaggio Beverly 350 cc, mounted on a MOOG motion platform (Fig. 1). The rider could interact with the motorcycle using the throttle handle and two brake levers. The front and rear brake levers worked independently from each other. The rider's braking action was measured by reading the brake lever angles using an encoder. The brake lever angle was sent to a model of the hydraulic braking system, which computed the virtual braking torque applied to the wheels to slow down the simulated vehicle. The rider's steering input did not affect the virtual motorcycle in this experiment. An overview of the simulator is provided by Celiberti et al. (2016).

For safety reasons, participants had to wear a helmet and a protective jacket while riding the simulator. The helmet and jacket were also used to enhance the fidelity regarding the feeling of riding a motorcycle. Furthermore, a full-body safety harness was used to secure the participant to the motorcycle's frame.

#### 2.2.2. Head-mounted display

The virtual environment was shown to participants using a head-mounted display 'Oculus Rift Developer Kit 2' (SDK 0.4) at a rate of 30 frames per second. The binocular setting of Oculus providing stereo vision was used with an inter-pupillary distance of 64 mm. The urban virtual environment was modeled using the PreScan simulation software. A speedometer was presented at the bottom of the displayed image.

The head-mounted display was mounted on a helmet, and the external camera was mounted on a pole attached to the platform in front of the motorcycle mock-up (Fig. 1). This external camera tracked the headset position and was used in conjunction with an inertial measurement unit in the headset to create a visual field that takes head motion into account (Oculus, 2014). Ideally, the visual image is not affected by the motion of the platform, and the visual orientation remains the same in both the no-motion and motion simulator configurations. The Oculus Rift uses sensor fusion to combine the data measured by the tracking camera and the inertial unit embedded in the Oculus. Even though the camera was fixed with respect to the motion system of the simulator, the measurement of the inertial unit affected the orientation of the rider view. This effect has been measured by fixing the Oculus with respect to the camera while moving the simulator as in the real experiment (Fig. 2 left). The results (Fig. 2 right) showed that, in the motion configuration, the visual orientation computed with the sensor fusion algorithm of the Oculus Rift is following the simulator's physical angle, introducing a visual pitch as if the rider would be looking downward/upward during braking/accelerating maneuvers. This effect does not occur for the no-motion configuration.

#### 2.2.3. Riding configurations

In the motion configuration, the motorcycle model provided feedback to the motion base. A traditional washout motion filter was applied using pitch (forward rotation) to simulate sustained acceleration (see the Supplementary Materials for the motion filter parameters). The

**Table 1**

Riding experience in the last 12 months.

Riding frequency	Never	Less than once a month	Once a month to once a week	1–3 days a week	4–6 days a week
Number of participants	2	4	2	2	2
Yearly kilometers	0	1–500	501–1000	1001–5000	10,001–20,000
Number of participants	2	4	3	2	1

**Fig. 1.** The MOTORIST simulator with a rider wearing an Oculus Rift and safety equipment.

motion reference point (also called ‘center of rotation’) was located approximately at the position of the rider’s head. In the no-motion configuration, no motion cues were provided by the motion platform. Head rotation was possible around three axes in both simulator configurations.

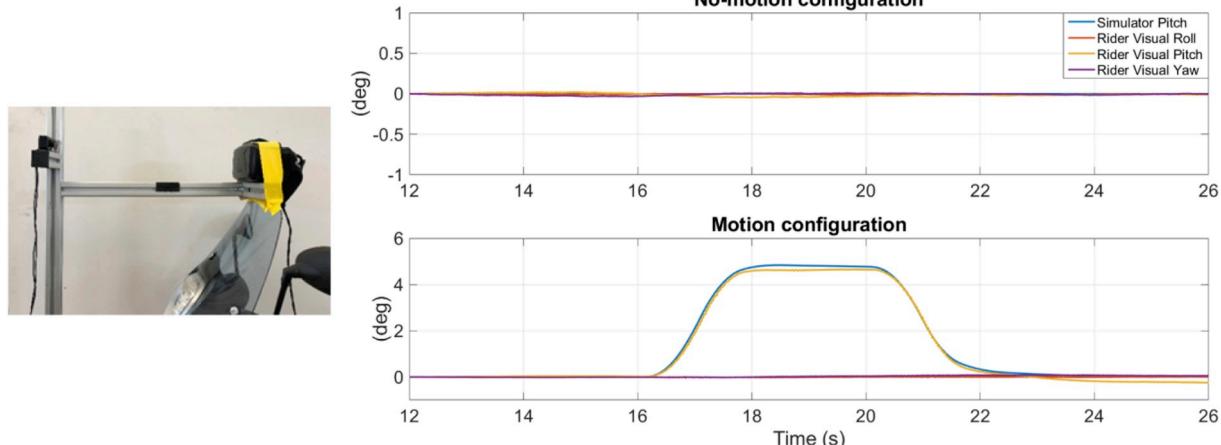
### 2.3. Stimuli

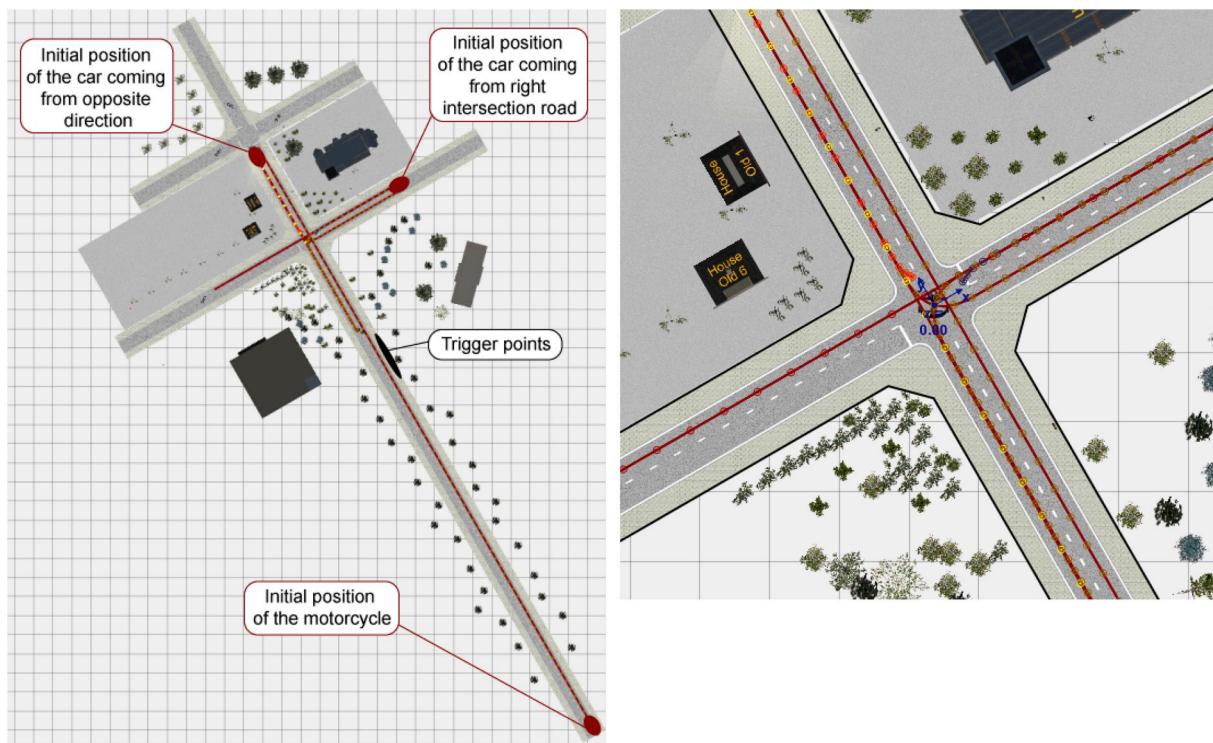
The simulated urban environment consisted of a two-lane straight road, where after approximately 295 m, the rider arrived at a four-way

intersection at which a car was always encountered. The speed limit was 50 km/h, and a priority sign was placed before the intersection. The lane width was 3.5 m, and 3 m wide sidewalks were present on both sides of the road. Small visual obstructions were present in the form of trees before the intersection. The same urban virtual environment was used for the practice and experimental sessions, see Fig. 3 for a top view of the intersection.

Three independent variables were manipulated to create nine different intersection situations:

- (1) *Car’s direction of travel.* The car could approach the intersection:
  - (a) from the opposite direction on the main road (‘From opposite’), or
  - (b) from the right side road (‘From right’).
- (2) *Car’s motion.* The speed profile of the car and car’s heading were programmed to create three intersection encounters (see Fig. 4 left). This variable was crossed with the car’s direction of travel variable, resulting in six intersection situations.
  - (a) *The car continues straight (‘Straight’).* The car was triggered at a speed of 40 km/h, and it did not decelerate. This was a safe situation if the car approached from the opposite direction, and an impending-crash situation if the car approached from the right. A crash would occur unless the participant braked hard.
  - (b) *The car begins a left turn and stops (‘Stops’).* The car was triggered at a speed of 40 km/h, and it decelerated to 0 km/h. This was a near-miss for both directions of travel of the car, as the car came to a stop just before making the turn.
  - (c) *The car turns left (‘Turns’).* The car was triggered at a speed of 40 km/h, and it decelerated to 20 km/h before making the turn. This was an impending-crash situation for both directions of travel of the car. In case the car came from the opposite direction of the main road, a crash would occur unless the participant braked hard.

**Fig. 2.** Left: Support used to fix the Oculus with respect to the tracking camera. Right: The visual orientation computed with the Oculus Rift SDK remains constant during the no-motion configuration, whereas the visual orientation is affected by the simulator motion. The introduced pitch angle in the visualization follows the angle of the motion system as if the rider would be looking downward/upward during braking/accelerating maneuvers. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)



**Fig. 3.** Left: Top view of the simulated world. The trajectories of the car and motorcycle are depicted as red lines on the road. Right: Zoomed-in view. The differently colored circular markers (yellow, red, light brown, dark brown) distinguish the different trajectories of the car. The motorcycle approached from the south and always drove in the center of the right lane. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

- (3) *Car's indicator.* Due to low visibility of the actual indicator light in the virtual world, the left headlight was used as an indicator only in the three 'car from the opposite direction' situations creating three additional intersection situations (see Fig. 4 right, situation 'From opposite, Stops (I)'). The indicator was either
  - (a) *on* (abbreviated I), or
  - (b) *off*.

The cars were triggered when the rider was at a certain distance from the intersection (see Fig. 4 left for trigger points). The car behaved in a pre-programmed manner and did not adjust its behavior to the participant's motorcycle in any way. If a participant collided with the car, the simulation continued, and the participant did not receive any collision feedback. The simulation of each intersection situation stopped either approximately 50 m after the intersection or when a participant came to a stop. At the end of each intersection situation, the rider was placed back in the initial position.

#### 2.4. Procedure

The experiment was conducted at the Siemens PLM Software facilities, Belgium. Before the simulator sessions, a consent form was signed, and the participants completed an intake questionnaire. The intake questionnaire consisted of items on demographic characteristics, riding and driving experience, and a baseline questionnaire on simulator sickness. See Fig. 5 for the experimental timeline.

Participants conducted two practice sessions to familiarize themselves with the simulator controls, visual stimuli (e.g., triggered cars), and the emergency braking task. Riders were informed about the nine intersection situations in the consent form, and they experienced them during the practice sessions. Each practice session consisted of nine different intersection situations presented in random order. The first practice session was conducted in the no-motion configuration and the second practice session in the motion configuration.

Following the two practice sessions, a participant completed 54 different repetitions of the intersection situations (9 intersection situations x 3 repetitions x 2 simulator configurations), divided into six sessions. Similar to the practice sessions, each testing session consisted of nine different intersection situations presented in random order and lasted approximately 8 min. Two blocks of three no-motion and three motion configuration sessions were created and counterbalanced across participants.

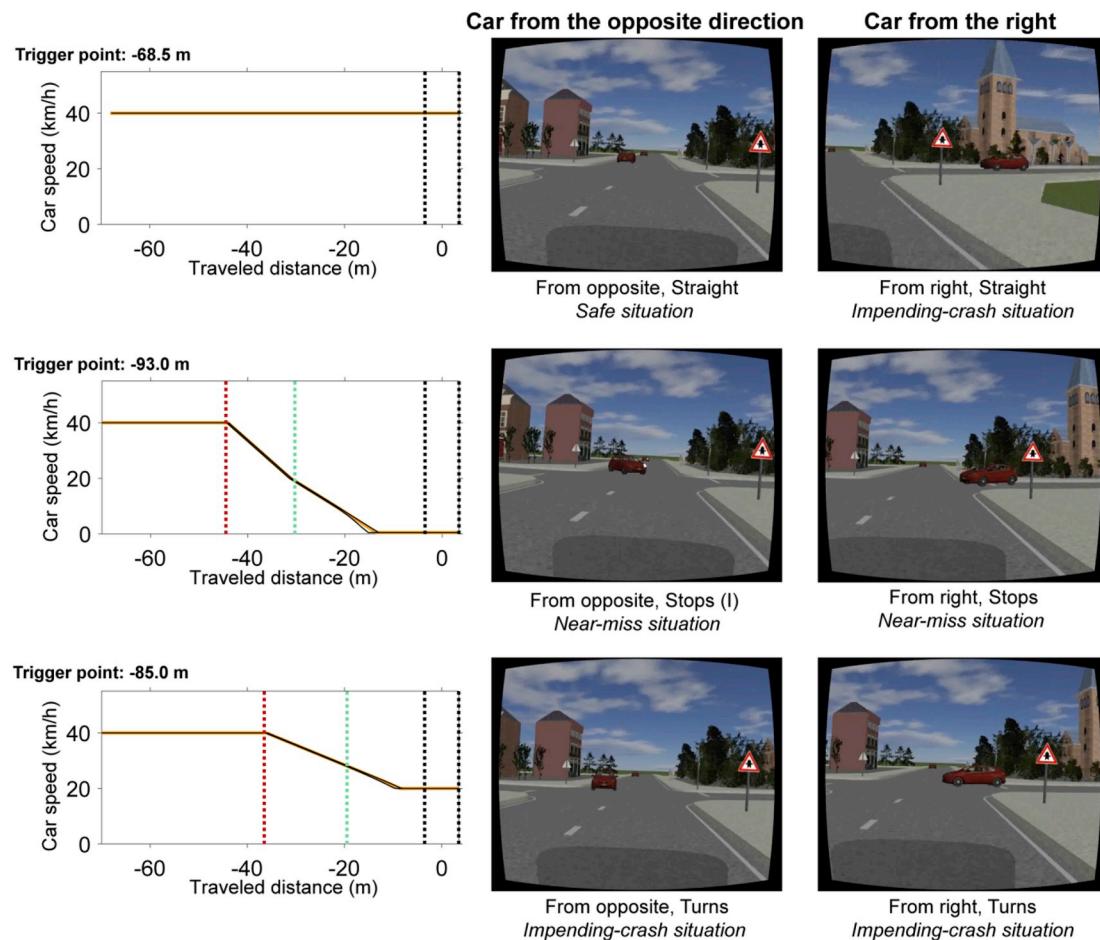
At the beginning of each trial, the participant was asked to hold the throttle to indicate that the simulation could start. The motorcycle automatically accelerated to 50 km/h, and this speed was maintained using cruise control until the rider started to brake. The throttle position did not influence the simulation when the motorcycle was already moving. When the rider started to brake and did not come to a full stop, the PTW automatically accelerated back to 50 km/h if the brake was fully released. Participants' task was: 'You will be riding 50 km/h, try to keep this speed as long as you can and brake only when needed to avoid a crash'.

After each session, simulator sickness was measured using the Misery Scale (MISC; Bos et al., 2005) and by the item on experienced oculomotor discomfort from the Simulator Sickness Questionnaire (Kennedy et al., 1993). The NASA Task Load Index (NASA TLX; Hart and Staveland, 1988) was administered three times during the experiment; once after the practice sessions, and twice after the no-motion and motion blocks. The entire experiment took approximately 2 h per participant.

#### 2.5. Measures

##### 2.5.1. Riding performance measures

The braking signal was averaged across the front and rear brake levers, in order to obtain an index of total braking input, where 100% represents the maximum value possible (occurring when braking 100% at the front and at the rear). A threshold of 3% of the average brake signal was used to distinguish braking from non-braking. The following



**Fig. 4.** Left: Car speed profiles and trigger points (distance between the motorcycle and the center of the intersection when the car was spawned). The black vertical lines indicate the start and end of the intersection, the red vertical line indicates the moment the approaching car started to decelerate, and the green vertical line indicates the moment when the heading of the approaching car started to change. Right: Screenshots of six intersection situations as observed by the participant. The speedometer (which was presented at the bottom of the displayed images) is not included in these screenshots. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

measures were calculated as an average across available trials per intersection situation per person.

**Brake initiation moment (m).** This measure describes the moment of braking, expressed as the participant's distance to the center of the intersection at the moment the participant pressed the brakes. We used distance (m) instead of elapsed time (s) for the sake of interpretability regarding situational events such as trigger points of the car. However, it is noted that distance can readily be converted to time because the participant's motorcycle had a constant approach speed of 50 km/h. This measure was calculated for a traveled distance between 70 m before the intersection and the entrance to the intersection located 3.5 m before the center of the intersection.

**Minimum riding speed (km/h).** This measure describes the minimum riding speed while approaching the intersection (i.e., before a potential collision with the car). This measure was calculated for the same travel distance as the previous measure. Speed data were logged until approximately 2 km/h, after which a trial ended.

**Maximum brake position (%).** The maximum brake position was used as an index of how hard riders decelerated. This measure is the maximum percentage of the rider's braking. This measure was calculated for a distance between -70 m and -3.5 m before the center of the intersection.

**Brake rise distance (m).** This measure represents the rider's braking style. It describes the traveled distance between the initiation of braking (threshold at 3%, as above) to the maximum brake position before the

rider entered an intersection.

**Percentage of trials with a stop (%).** This measure indicates whether the rider came to a stop before entering the intersection. This measure was calculated for each of the four impending-crash intersection situations separately. We used a threshold of 5 km/h to distinguish stopping from not stopping.

**Percentage of trials with a crash (%).** The crash percentage was calculated using the distance between the centers of two vehicles in the virtual world. If this distance was below 2.4 m, a crash was recorded. The percentage of crashes was calculated for the four impending-crash intersection situations.

#### 2.5.2. Self-reports

**Simulator sickness (0–10).** The 11-point MISC (Bos et al., 2005) and an item on oculomotor discomfort "I experience oculomotor discomfort at the moment (eyestrain, difficulty focusing, blurred vision or headache)." (Kennedy et al., 1993) were provided to participants to monitor the development of simulator sickness during the experiment. The MISC ranges from *no problems* (0) to *vomiting* (10). The experienced oculomotor discomfort was rated on a scale from *not at all* (0) to *very much* (10). If the participant reported a score of 6 or higher on one of these items, the experiment was interrupted, and either a longer break was taken by the participant or the participant withdrew from the experiment.

**NASA TLX (1–21).** The six-item NASA TLX questionnaire was used to



**Fig. 5.** The experimental timeline. The orange blocks consisted of either three no-motion or three motion configuration sessions and were counterbalanced across participants. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

assess riders' workload. The questionnaire contained items on mental demand, physical demand, temporal demand, performance, effort, and frustration (Hart and Staveland, 1988). Items were rated on the 21-point scale ranging from *very low* (1) to *very high* (21) and *failure* (1) to *perfect* (21) for the performance item.

### 3. Results

One female and one male participant withdrew from the motion test sessions because of experiencing severe nausea and medium oculomotor discomfort during the first motion test session. The female participant had completed two no-motion sessions, and the male participant had completed all three no-motion sessions without experiencing severe discomfort. Therefore, these two participants were included in the analysis for the no-motion configuration only. Another female participant experienced severe nausea and severe oculomotor discomfort during the last motion test session. This participant was included in the analysis for both the no-motion and motion conditions; only data from the last (sixth) session were excluded. Further, a data quality check revealed that there was a data logging error in the last no-motion session for one participant and in one motion trial for another participant. Results reported below are based on 306 trials completed in the no-motion configuration and 260 trials completed in the motion configuration.

#### 3.1. Self-reported simulator sickness and experienced workload

There were no significant differences in experienced motion sickness and oculomotor discomfort between the two simulator configurations among ten participants who completed trials for both configurations (Table 2). The self-reported mental demand, physical demand, and

effort were significantly higher for the motion condition as compared to the no-motion condition.

#### 3.2. Effect of visual stimuli on riders' speed and braking performance

Riders initiated braking in 16.7% of the 126 safe situation trials in which the car from the opposite direction drove straight ahead, in 50.5% out of 188 near-miss trials where the car performed an emergency stop, and in 98.0% out of 252 impending-crash trials in which the car drove into the path of the rider.

**Fig. 6** shows that the riders did not brake immediately after the car approaching from the opposite direction started to decelerate (top and middle rows). Instead, the riders started to initiate braking right after the car started to change its heading. On average, riders initiated braking further from the intersection in 'car stops' situations as compared to the 'car turns' situations (Table 3).

##### 3.2.1. Car's indicator

Riders initiated braking on average 3.94 m (in 'Stops' situations) and 2.15 m (in 'Turns' situations) earlier when the car from the opposite direction indicated the turn as compared to when the car did not (Table 3). The average riding speed while approaching the intersection was similar for both indicator conditions (Fig. 7).

The effect of the indicator on the brake initiation moment was not statistically significant for the 'car turns' situations ( $t(11) = 0.50$ ,  $p = 0.627$  and  $t(9) = 1.50$ ,  $p = 0.169$  for the no-motion and motion configurations, respectively). The effect of the indicator on the minimum riding speed in the 'car turns' situations was not significant either ( $t(11) = 0.27$ ,  $p = 0.791$  and  $t(9) = 0.93$ ,  $p = 0.377$  for the no-motion and motion configurations, respectively). The *t*-tests were not conducted for the 'car stops' situations due to the low number of braking events.

Although riders braked in the 'car turns' situations, they still often crashed into the car (Table 4). The percentage of crash involvement was slightly lower in situations when the car indicated a turn compared to situations when the car did not indicate the turn.

##### 3.2.2. Car's direction of travel

When the car approached the intersection from the right and turned ('From right, turns'), riders on average braked 9.34 m earlier compared to the situation where the car approached from the opposite direction and turned ('From opposite, turns'). This effect, which can be seen in Fig. 6 (bottom middle vs. top middle), was significant ( $t(10) = 4.79$ ,  $p < 0.001$  and  $t(9) = 5.61$ ,  $p < 0.001$  for the no-motion and motion configurations, respectively). As can be seen in Table 4, riders were less likely to come to a stop before entering an intersection when the car approached from the opposite direction as compared to situations when the car approached from the right intersecting road.

#### 3.3. Comparison of braking performance between the motion and no-motion configurations

**Fig. 6** shows the mean brake position and Table 3 shows the means and standard deviations of the brake initiation moment, maximum brake position, and the distance from initiating of braking to the point of maximum braking (i.e., brake rise distance) for the two motion configurations. The results of paired sample *t*-tests did not show a significant effect of simulator motion on the maximum brake position ( $p > 0.215$  for each of the nine situations) nor on brake rise distance ( $p > 0.131$  for each of the nine situations). Lastly, no substantial differences were observed in the initiation of the braking maneuver between the motion and no-motion configurations ( $p > 0.022$  for each of the nine situations).

Further illustration for the lack of effect of motion is provided in Figs. 8 and 9. Fig. 8 shows the maximum brake position for the nine intersection situations. It can be seen that the effect of situation is stronger than the effect of motion; the correlation between the values for the two configurations was close to unity ( $r = 0.99$ ,  $N = 9$ ). Fig. 9 shows

**Table 2**

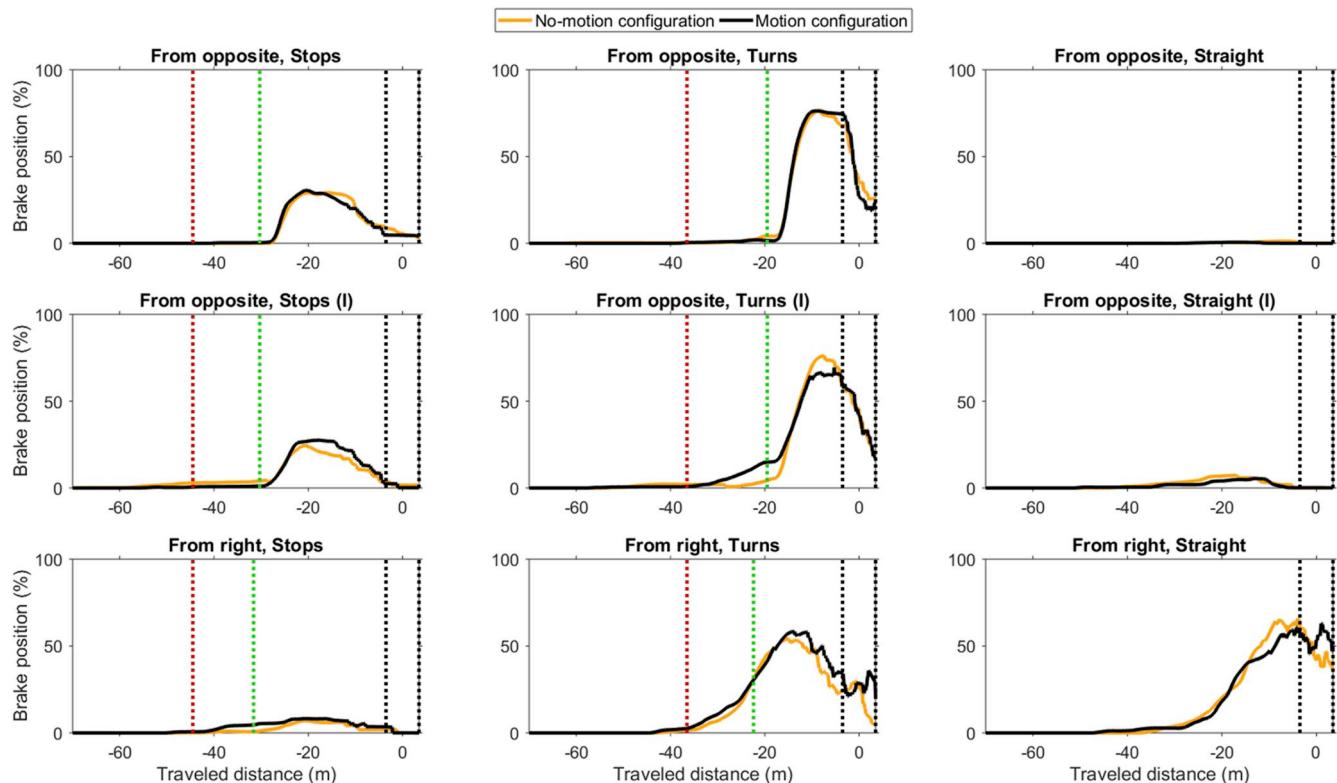
Minima, maxima, means, standard deviations, and results of paired sample *t*-tests for self-reported simulator sickness and NASA TLX per simulator configuration for the 10 participants who completed both simulator motion configurations.

	No motion			Motion			No motion vs. motion	
	Min	Max	Mean (SD)	Min	Max	Mean (SD)	<i>t</i> (df)	<i>p</i>
Sickness (0–10) <sup>a</sup>	0	4.33	1.00 (1.40)	0	4.67	1.47 (1.90)	-1.26 (9)	.240
Oculomotor discomfort (0–10) <sup>a</sup>	0	5.00	1.50 (1.86)	0	5.00	1.77 (1.87)	-1.10 (9)	.299
NASA TLX: Mental demand (1–21) <sup>b</sup>	3	7	4.40 (1.43)	3	11	5.90 (2.96)	-2.29 (9)	<b>.048</b>
NASA TLX: Physical demand (1–21) <sup>b</sup>	1	12	4.90 (3.03)	3	20	8.50 (5.84)	-2.66 (9)	<b>.026</b>
NASA TLX: Temporal demand (1–21) <sup>b</sup>	3	12	5.30 (2.71)	3	14	6.30 (3.62)	-2.24 (9)	.052
NASA TLX: Performance (1–21) <sup>b</sup>	5	17	10.80 (4.21)	6	17	11.60 (3.89)	-1.31 (9)	.223
NASA TLX: Effort (1–21) <sup>b</sup>	3	15	8.20 (3.99)	3	16	9.90 (5.04)	-2.85 (9)	<b>.019</b>
NASA TLX: Frustration (1–21) <sup>b</sup>	1	14	5.10 (4.33)	1	16	4.80 (4.66)	0.90 (9)	.394

Notes. P-values < 0.05 are shown in boldface.

<sup>a</sup> Asked after each session.

<sup>b</sup> Asked after each block, i.e., three sessions.



**Fig. 6.** Mean brake position (front and rear brake averaged) during the nine intersection situations per simulator motion configuration. In case a participant came to a stop, data are not shown further. The black vertical lines indicate the start and end of the intersection, the red vertical line indicates the moment when the approaching car started to decelerate, and the green vertical line indicates the moment when the heading of the approaching car started to change. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

a bimodal distribution of the maximum brake position; participants either braked hard or did not brake, with relatively few instances of mild braking (5–40%).

#### 4. Discussion

Accident statistics show that a frequent crash scenario involving a PTW rider is a crash with a car at an intersection (Clarke et al., 2007; MAIDS, 2009). An in-depth investigation of PTW-car accidents showed that car drivers often failed to perceive the oncoming motorcycle, whereas the PTW riders failed not only in perception but also in executing an avoidance maneuver, such as too weak braking (Penumaka et al., 2014). To study this issue from the perspective of the PTW rider, we performed a simulator study that compared riders' braking performance for impending-crash, near-miss, and safe intersection situations.

The results showed that riders initiated braking right after the car from the opposite direction made a heading change that could signal an imminent threat. The riders initiated braking later (i.e., when they were closer to the intersection) in impending-crash situations compared to near-miss situations. This finding can be explained by the fact that riders appeared to brake immediately after a change in the car's heading, which occurred earlier in near-miss situations than in the impending-crash situations.

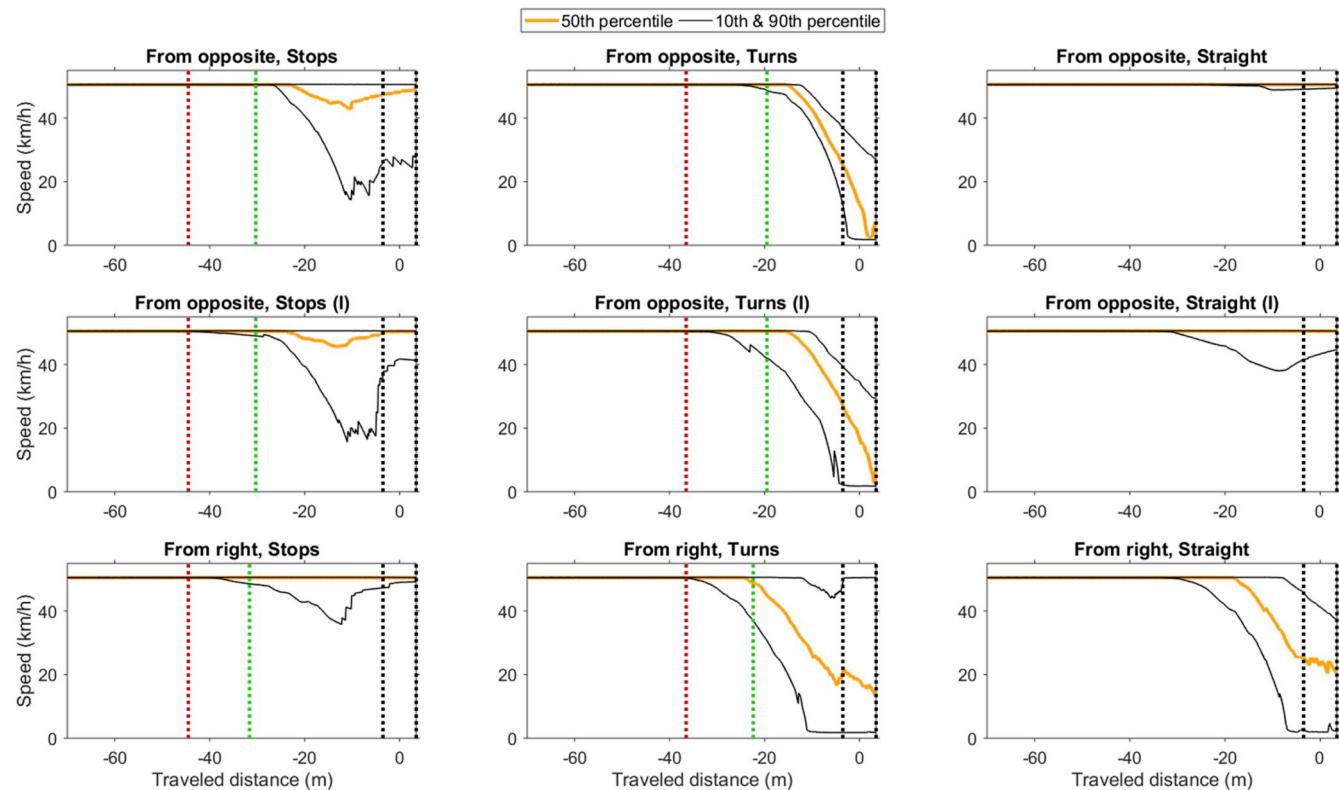
Results further indicate that, in situations where a car driver suddenly initiates a left turn, riders are often unable to avoid a collision. It should be noted, however, that the approach speed was fixed at 50 km/h and riders were instructed to try to keep this speed as long as they could and brake only to avoid an upcoming crash. Crundall et al. (2013) showed that expert riders tend to slow down when approaching an intersection, indicating that not only 'bottom-up' visual cues but also

**Table 3**

Means and standard deviations of the brake initiation moment, minimum riding speed, maximum brake position, and brake rise distance for nine intersection situations per simulator motion configuration.

	Brake initiation moment (m)				Minimum riding speed (km/h)				Maximum brake position (%)				Brake rise distance (m)			
	No motion		Motion		No motion		Motion		No motion		Motion		No motion		Motion	
	Mean (SD)	n	Mean (SD)	n	Mean (SD)	n	Mean (SD)	n	Mean (SD)	n	Mean (SD)	n	Mean (SD)	n	Mean (SD)	n
From opposite, Stops <sup>nm</sup>	-25.19 (1.98)	9	-25.75 (3.45)	8	34.48 (17.06)	12	33.71 (20.34)	10	36.91 (28.50)	12	33.82 (32.72)	10	6.97 (2.67)	9	4.49 (2.55)	8
From opposite, Turns <sup>ic</sup>	-17.80 (5.28)	12	-17.94 (4.31)	10	24.31 (10.01)	12	25.27 (7.83)	10	78.91 (15.26)	12	77.39 (16.00)	10	9.26 (5.37)	12	9.33 (5.86)	10
From opposite, Straight <sup>s</sup>	-18.87 (7.32)	2	-23.95 (3.89)	2	50.02 (0.97)	12	50.23 (0.50)	10	1.61 (3.83)	12	0.73 (1.32)	10	6.45 (1.48)	2	4.50 (1.13)	2
From opposite, Stops (I) <sup>nm</sup>	-30.24 (11.24)	9	-28.58 (10.31)	7	34.47 (18.69)	12	33.05 (19.66)	10	31.89 (30.20)	12	30.47 (33.23)	10	9.37 (6.59)	9	7.44 (5.70)	7
From opposite, Turns (I) <sup>ic</sup>	-18.45 (5.59)	12	-21.59 (10.70)	10	23.81 (12.03)	12	21.57 (10.01)	10	78.07 (15.99)	12	75.61 (16.26)	10	8.81 (4.92)	12	11.44 (8.31)	10
From opposite, Straight (I) <sup>s</sup>	-29.83 (6.56)	4	-24.44 (11.08)	4	45.50 (13.22)	12	48.10 (4.54)	10	8.00 (16.98)	12	7.15 (11.19)	10	8.84 (7.42)	4	6.58 (6.50)	4
From right, Stops <sup>nm</sup>	-33.51 (6.90)	5	-39.50 (4.28)	4	46.20 (9.71)	12	43.55 (12.44)	10	8.32 (17.36)	12	10.39 (18.90)	10	6.26 (3.17)	5	12.90 (8.26)	4
From right, Turns <sup>ic</sup>	-26.83 (5.65)	11	-27.60 (7.07)	10	17.23 (14.02)	12	10.92 (8.50)	10	61.00 (25.59)	12	70.19 (21.26)	10	12.22 (5.85)	11	12.57 (9.54)	10
From right, Straight <sup>ic</sup>	-19.37 (7.31)	12	-20.15 (9.99)	10	20.39 (14.08)	12	22.89 (17.00)	10	77.14 (16.95)	12	73.98 (19.99)	10	10.19 (4.82)	12	10.66 (6.20)	10

Notes. '(I)' the car was indicating a turn, 's' safe situation, 'nm' near-miss situation, 'ic' impending-crash situation.



**Fig. 7.** Median, 10th percentile, and 90th percentile of speed across trials per intersection situation. In case a participant came to a stop, data are not shown further. The black vertical lines indicate the start and end of the intersection, the red vertical line indicates the moment when the approaching car started to decelerate, and the green vertical line indicates the moment when the heading of the approaching car started to change. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

'top-down' expectancies guide riders' behavior. A similar account is provided by Summala and Rasanen (2000), who illustrated the interaction of top-down factors and bottom-up factors leading up to cyclist-driver crashes. The results from our study suggest that such precautionary strategies are essential for safety, as a purely detective/reactive behavior of the rider is not enough to avoid a collision.

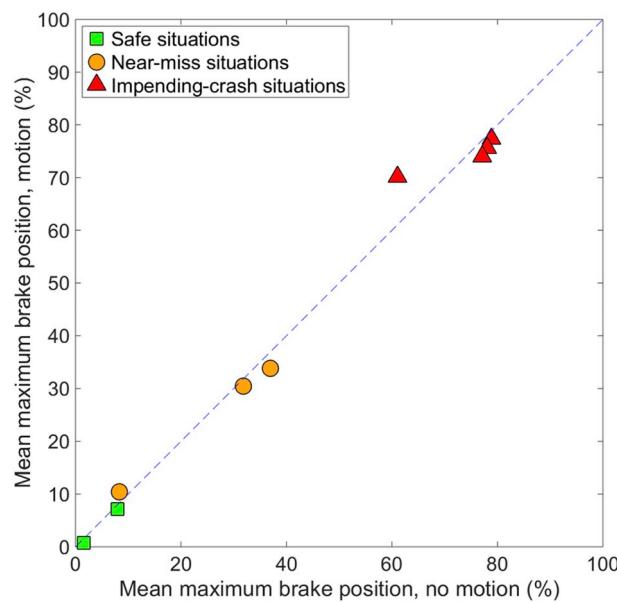
In line with the findings from previous studies on the importance of car's indicator (Huertas-Leyva et al., 2017; Lee and Sheppard, 2016), riders initiated their braking maneuver slightly earlier when the car was indicating the turn as compared to when the indicator was off. However, the motion of the car and change of heading had stronger effects on the initiation of braking than the indicator signal, as inferred from the fact

**Table 4**

Percentage of trials when riders came to a stop (threshold at 5 km/h) before entering the intersection and percentage of trials in which riders were involved in a collision for the four impending-crash situations.

	From opposite, Turns		From opposite, Turns (I)		From right, Turns		From Right, Straight	
	Stop	Crash	Stop	Crash	Stop	Crash	Stop	Crash
No motion	8.82%	76.47%	17.65%	73.53%	50.00%	0.00%	32.35%	8.82%
Motion	0.00%	79.31%	24.14%	65.52%	62.07%	0.00%	31.03%	20.69%

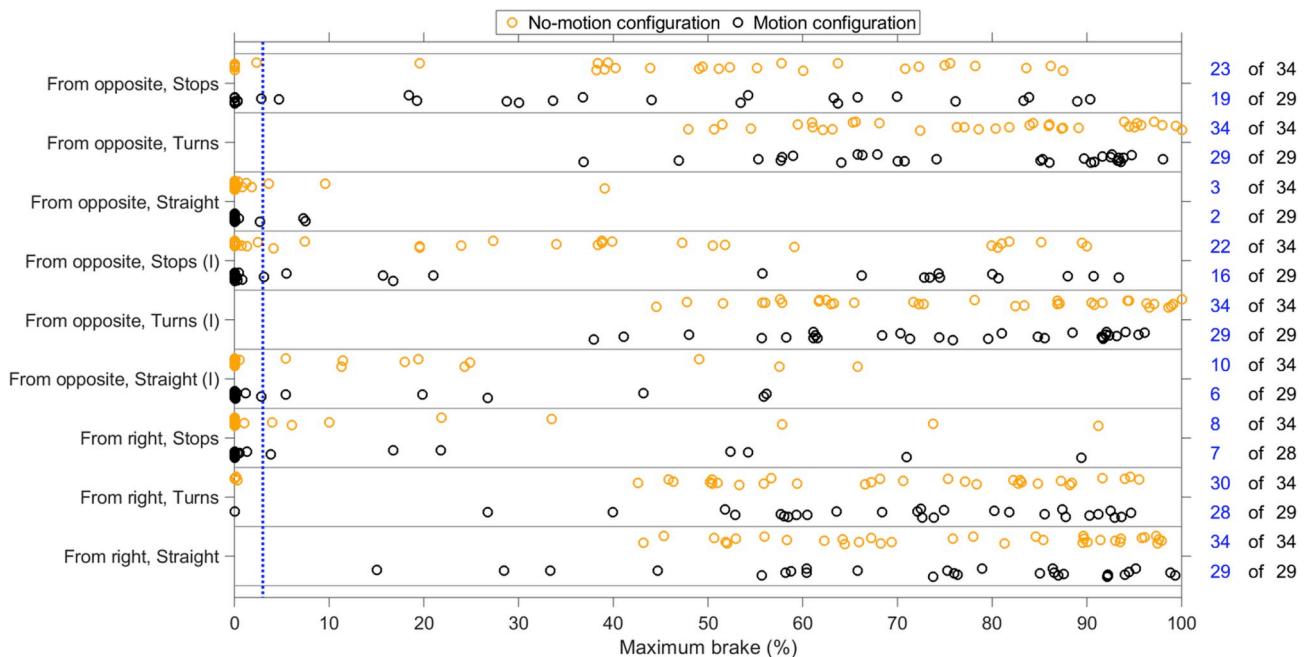
Notes. (I) – The car was indicating a turn. A crash in the ‘From right, Turns’ situation could not happen because this car was triggered at the same time as the cars in ‘From opposite, Turns’ situations as a result of which the potential collision point was located further down the road.



**Fig. 8.** Mean maximum brake position for the nine scenarios shown in Table 3, for the no-motion configuration and the motion configuration. The diagonal dashed line is the line of unity.

that riders were unlikely to brake in safe situations even if the turn signal was on. According to the instructions that we provided, participants should not brake when the car continued straight or stopped. In other words, the indicator had to be ignored in these two situations. The effect of the indicator could be smaller in our study as compared to on-road riding because, in reality, the cars’ indicator would guide the rider’s expectancies and thereby cause the rider to slow down. Furthermore, we note that in real-life cases, riders may be able to anticipate what other road users will do, not only based on the turn indicator but also with the help of other types of precursors or foreshadowing elements (Underwood et al., 2011; Vlakveld, 2014). Examples of such precursors, which were not simulated in our study, include the pre-positioning of the lateral position of the car, additional conflicting vehicles, road markings, head orientation, and eye contact. Future research could employ a more varied visual environment in which multiple road features (e.g., signs, lights, multiple road users) are present, thereby placing high demands on anticipation skills.

Riders initiated their braking maneuver in crash situations earlier when the car was approaching from the right compared to situations when the car approached the intersection from the opposite direction. This effect corresponds to the relatively high percentage of stops before the intersection in the ‘car from right’ situations. One plausible explanation is that the car from the right is on a collision course with the rider, whereas the car coming from the opposite direction is on a collision course only when it turns to its left. Accordingly, in the car-from-opposite situations, the riders started to brake only when visual



**Fig. 9.** The maximum brake position prior to entering the intersection. Each marker represents a single trial. Blue numbers represent the number of trials in which participants pressed the brakes (threshold at 3% brake input). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

information such as the car's indicator or heading in combination with high speed could be observed.

The second aim of this research was to compare riders' braking performance when longitudinal motion cues are provided by a motion platform compared to a no-motion simulator configuration. Our results did not show detectable effects of motion on the riders' braking behavior. This result appears to contradict literature that indicates that drivers brake more smoothly when motion cues are enabled as compared to when they are disabled (e.g., De Groot et al., 2011; Siegler et al., 2001) as well as more general studies showing that simulator motion can have strong effects on driving behavior (Berthoz et al., 2013; Shyrokau et al., 2018).

Apart from statistical power, three possible explanations for the discrepancy between our results and the literature can be thought of. First, because the riders approached the intersection using cruise control and steering input did not affect the virtual motorcycle, motion cues were unavailable before the rider started to brake in both the no-motion and motion conditions. This means that the effects of motion on the riders' risk perception and subjective presence in the virtual environment may have been limited; only after the rider started to brake, he/she could feel the motion. Second, we showed that the riders' decisions were rather binary: short-lasting hard braking or no braking (Fig. 9). This observation ties into theories about open-loop versus closed-loop manual control (Jagacinski and Flach, 2003). In particular, if riders "slam on the brakes to avoid a collision" (Jagacinski and Flach, 2003, p. 67), no association between braking control and motion feedback ought to be expected. A third explanation for the lack of observable motion effects concerns the motion cueing algorithm itself. It is possible that our adaptive filter-based algorithm as detailed in the Supplementary Materials yielded a too sluggish response for the highly dynamic braking maneuver under investigation. Thus, the lack of effect by no means implies that motion would not have effects for other types of riding/driving tasks and other types of motion drive laws. It remains to be investigated whether motion affects closed loop braking behavior. This research question could be studied in non-emergency tasks such as approaching an intersection where a rider does not have the right of way or before entering a turn.

Several limitations should be considered when interpreting the present results. First, only 12 people participated, raising questions about statistical power (i.e., 1 minus the false-negative rate), false positives (Button et al., 2013), and generalizability. The small sample size is a concern for the results for the turn indicator, where significant effects may plausibly be expected if larger samples were used. On the other hand, some of the other observed effects presented in this paper are very strong and may not require larger samples. Specifically, the effects concerning the car's direction of travel on the participant's behavior were strong and significant ( $p < 0.001$ ), suggesting high replicability. Also, the finding that motion increases self-reported physical demands and effort is interpretable from a biomechanics viewpoint and thus expected to be replicable. Also, the fact that participants in near-miss scenarios braked harder as compared to safe scenarios, but less hard as compared to impending-crash scenarios, is interpretable and strong, with little overlap of distributions (see also Fig. 7). In summary, we argue that the present sample size is a limitation for some of our findings (e.g., effect of the indicator), but still sufficient for our primary research purposes. It should be reminded that our type of research involves ethical and safety challenges regarding motion sickness after-effects (Brooks et al., 2010; Dziuda et al., 2014). Hence, we would advise other researchers not to test more participants than needed if they were to conduct this type of research. The current results show a learning curve where participants grew accustomed to the fact that they did not have to brake in the safe situations, and gradually braked less hard in the near-miss and impending-crash situations (Supplementary Materials, Fig. S4). It would be interesting to examine how these trends develop in an even larger number of trials.

A second limitation is that our study aimed to investigate whether

riders are capable of avoiding a potential collision based on 'bottom up' visual cues in situations where a crash could be expected. In reality, situations in which a car driver does not give right of way are encountered only rarely. Instead, on the road, riders may show a later initiation of braking in case the situation is not expected by the rider (Green, 2000; Olson and Sivak, 1986) as well as anticipatory braking before the relevant visual cues are available. More research should be conducted to understand to what extent a precautionary approaching strategy could significantly reduce the number of crashes.

Third, the realism of the simulator deserves further consideration. Future research could employ a more realistic PTW dynamics model, allowing for the in-depth examination of brake modulation of the front and rear brakes and motorcycle stability in emergency braking conditions (for models see Corno et al., 2008; Limebeer et al., 2001). The virtual environment built in PreScan and projected in the Oculus Rift DK2 resulted in a limited screen resolution. For this reason, the car's headlight had to be used instead of the car's indicator light. This limitation is relatively easily countered in future research, as the resolution and refresh rate of the head-mounted display is rapidly increasing (e.g., Vieri et al., 2018). Future research could also use richer virtual environments in order to examine the effect of the aforementioned hazard precursors, although it remains to be seen whether higher visual fidelity would improve the validity of research data (Lee, 2004).

## 5. Conclusions and recommendations

In conclusion, riders' braking patterns differed between impending-crash, near-miss, and safe situations: the more dangerous the situation, the more likely riders were to brake and the harder they braked. Riders appear to brake in response to a deviation in the approaching car's heading. Additionally, we showed that riders were often unable to avoid a collision with the car in impending-crash conditions.

Possible remedies to PTW-car crashes could be adjustments in road design (e.g., the presence of a left-turn lane), automated emergency braking for PTWs (Savino et al., 2016), and vehicle-to-vehicle communication technologies for providing warnings in advance (Houtenbos et al., 2017). Furthermore, we see an opportunity for our results to be used in risk awareness training programs (cf. Pollatsek et al., 2006). That is, it would be valuable for PTW riders to be taught, using a PC-based animation, in which cases crashes are unavoidable, and why it is important to slow down before intersections.

Although we did not observe a significant effect on rider's emergency braking performance between the two simulator configurations, it may be that this study concerned a particular task for which motion is not needed, or it may be due to the specific parameter settings of the motion cueing algorithm (Supplementary Materials). It remains to be investigated how motion cues provided by a hexapod would affect riding performance in tasks such as continuous braking or turning, where closed-loop control is to be expected.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.apergo.2019.102970>.

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