Development of a low-cost motorcycle riding simulator for emergency scenarios involving swerving

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Keywords

Motorcycle, riding simulator, validation, emergency manoeuvre, steering input

This is an Author's Original Manuscript of an article submitted for consideration in Proc IMechE Part D: J Automobile Engineering. The published paper is available online at http://pid.sagepub.com/content/early/2016/01/19/0954407015624998.abstract

Abstract

The development of advanced riding assistance systems requires the analysis of user reactions in emergency situations. Motorcycle riding simulators are an alternative to “on road” testing as in the virtual environment dangerous scenarios can be investigated without risks for the participants. In this paper, we propose a validation process of a low-cost motorcycle simulator characterised by: (i) elastic resistance on the steer input; and (ii) counter steer strategy. Sixteen riders tested the simulator in different manoeuvres, including cornering in non-urban environment, slalom and lane change. Objective and subjective evaluation showed good realism of the simulator, in particular for investigating lateral avoidance scenarios. The development of suitable motorcycle simulators will significantly advance the field of the motorcycle safety research.

Introduction

Motorcycles and mopeds, often referred to as Powered Two-Wheelers (PTWs), now number more than 300 million around the world and the number is likely to increase.[1] PTWs can play an important role for the current challenges of personal mobility at a global level,[2] despite the higher risk of death and serious injuries for PTW users when compared to other motorised vehicle users.[3] In the last two decades, new technologies have been proposed to improve PTW safety, including primary safety systems such as antilock braking, traction control, collision warning, and curve warning.[4-7] The effectiveness of some of these technologies, for example the warning systems, depends on the correct human-machine interaction which needs to be developed taking account of both user preferences and also user performance with the systems. In some cases, experiments with users have been carried out in the real world, especially in low risk activities.[7-12] Another approach used for practical testing involving users is via driving simulators, which allows evaluating the human reactions in demanding conditions with low risk for the participants.[6, 13] The involvement of simulator experiments in the development of safety technologies is documented for passenger cars,[14-17] and for trucks.[18] Simulator studies were also conducted to investigate unexpected emergency situations.[19, 20] Driving simulators have shown their value in studying driver behaviour and their wider adoption for motorcycle riding is desirable to investigate rider behaviour.

A critical aspect of any simulator is the level of fidelity that it can achieve in the driving context. In particular one aspect, functional fidelity (how the simulator behaves compared to how the user expects it to behave), is important – more important in fact than physical fidelity (how it looks).[16] The use of a simulator to inform the vehicle design process therefore requires adequate fidelity in the inputs provided to the user during the simulation in the specific test situation. If so, the feedback obtained from the user in the simulation is then assumed to be compatible with the feedback the same user would provide in the corresponding real-world situation.[21]

Producing appropriate functional fidelity is particularly challenging for motorcycle riding simulators, as documented in several validation studies available in the recent literature (see [22] for a review). A remarkable example of motorcycle simulator is the one developed by Cossalter, Lot [23]. It consisted in a five-degree of freedom motorcycle rig equipped with sensors measuring several inputs from the rider, including throttle and brake controls, steer torque input, gear shift, and lateral body position. The custom-built motion system was able to produce lateral shifts, roll, yaw, and pitch rotations, and active steer feedback. The dynamical engine of the simulator was a self-developed 14-degree-of-freedom multibody model with high physical fidelity.[24] Cossalter et al. presented a subjective and objective validation of their simulator in standard manoeuvres: acceleration and braking, steady cornering, lane change and slalom. Despite the high degree of physical agreement and the overall good level of satisfaction of the users, the subjective feedback provided by the riders indicated an incomplete agreement between simulated and real riding experience. In fact, the average ratings provided by the test users regarding the feel of the steering were between 3 and 4 in a scale from 0 to 5.

A different approach is to start from a simple simulator setup in order to identify the most important improvements to enhance fidelity. For example, a static-rig simulator based on a passenger car dynamical model was tested in BMW [25], showing the importance of realistic steering feedback. From a rider's viewpoint there are two common approaches to steering: positive steering (i.e. clock-wise steer angle to turn right, and vice versa), and counter steering (counter clock-wise steer torque to turn right and vice versa). Both strategies have a physical rationale: in steady state cornering the handlebar is typically rotated towards the inner of the curve (as in the positive steering), whereas counter steer torque is the typical strategy applied in a wide range of riding conditions.[26-29] Positive steering appeared more intuitive and allowed higher accuracy in the vehicle control. As a drawback, positive steering does not allow to measure realistic steering torques during the simulation. A combination of the two strategies is also possible, resulting in a more realistic simulation at the cost of a higher complexity [22].

Despite the various and well documented approaches to motorcycle simulation, current literature seems to lack a description of lower-cost yet realistic riding simulators.

In the attempt of filling this gap, the present paper describes the subjective and objective validation of a simple and low-cost motorcycle riding simulator adopting counter steer strategy. The aim of the simulator was to capture steering input timing, sign and magnitude in standard manoeuvres. The simulator was built within the EC funded project ABRAM to investigate the possible steering reactions of rider facing unexpected collision scenarios for the development of advanced safety systems for motorcycles.

Method

Apparatus

The motorcycle riding simulator was a low-cost upgrade of a simulator available at the Monash University Accident Research Centre (MUARC). The original simulator rig [30] consisted in a sports motorcycle (Honda NSR150), which provided realistic geometries for the riding position. In this rig, the steer, throttle and brake inputs were measured using the hardware of a commercial steering wheel system for gaming application. A timing belt and pulleys transmission operated an amplification of the steer angle between the front fork assembly and the steer shaft input of the gaming system (transmission ratio 1:3). The brake lever and pedal were connected with their original independent hydraulic systems to preserve a realistic feeling. The two brake controls were connected via Bowden cables to a single potentiometer, the output of which was used as brake input for the vehicle model. Different leverages on the pot side were adopted to mimic the different effectiveness of the front and rear brakes.

For the present research, the motorcycle weight was reduced by removing the engine, the rear wheel, the swing arm, and other ancillary components. The standard steering assembly was connected to the frame via two pre-loaded helical springs attached to a support mounted on the rim (Figure 1), to obtain an elastic torque in response to steer inputs in the form of rotations of the handlebar along the steering axis (equivalent elastic coefficient: 3.43 Nm/degree). The motorcycle frame was mounted on a commercial motion base consisting of three actuators (two in the front and one in the rear). The motion base produced bounce, pitch, and roll cues computed by the simulation software. A commercial electromagnetic shaker for home theatre application was connected to the frame under the original saddle, with vertical axis. The shaker was controlled via dedicated amplifier connected to the audio channel of the simulator in order to produce a vibration correlated with the engine sound.

The simulator rig was controlled by a desktop PC running the Eca Faros driving simulation software integrated with Carsim for the computation of the vehicle dynamics. The simulator software used the real time model of a passenger car instead of using a motorcycle model. The rationale for this choice was the initial ease of implementation to adapt the car simulator, assuming that the behaviour of a car model and a motorcycle model are similar for the manoeuvres and the range of speeds involved in the experiments. The reference vehicle was a 3 Series BMW passenger car with 3,000 cc capacity diesel engine, rear wheel drive, and automatic transmission. The simulator software computed the motion, auditory, and visual cues. The signal for the roll cue was inverted and amplified to account for the opposite tilting directions between a four- and two-wheeled vehicle. The visual cues were provided to the user via three Nec Multisync X-series screens (1.01 m x 0.58 m each), with total resolution of 5760x1080 and refresh frequency of 60 Hz, positioned 1.20 m off the user (horizontal field of view: 120 degrees). Standard, 3-channel desktop speakers delivered the audio cues.

The principal characteristics of the new motorcycle simulator were the following: (i) steering input with elastic feedback and implementing counter steer strategy; (ii) vehicle dynamics computed with the dynamical model adapted from a passenger car; (iii) motorcycle rig mounted on a motion base implementing inverted roll angle for lateral motion cues; (iv) no tilting horizon in the visual cue.

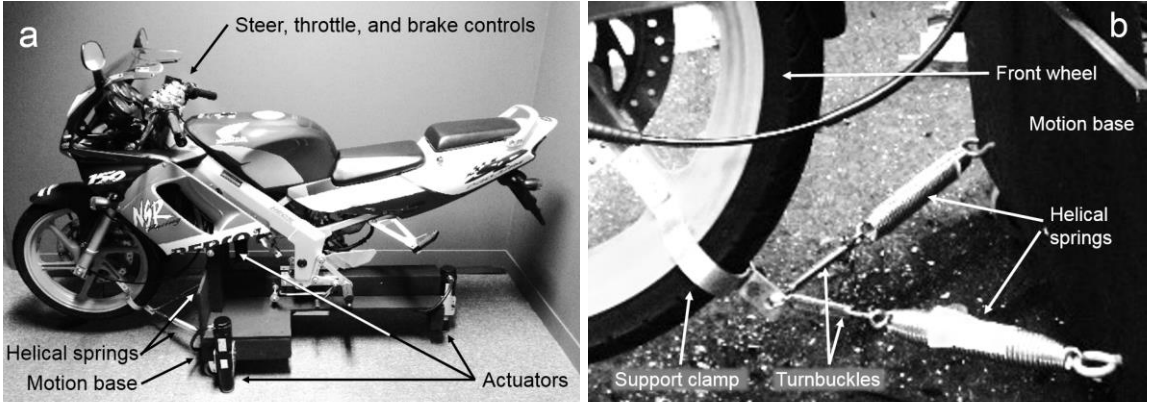


Figure 1. (a) Motorcycle rig. (b) Detail of the elastic connection linking the rim of the front wheel to the motion base.

Participants

Participation in this study involved attending the Advanced Driving Simulator facilities of MUARC for a single 1.5 hour testing session, with a reimbursement of AU$ 30. Riders in the age 20-65 years, holding a motorcycle licence, and riding at least once a week, were eligible for recruitment. Fifty-two people were identified from: (i) an existing database of participants who took part in previous road safety studies; (ii) University colleagues; and (iii) an advertisement in the University newsletter. Forty-five people were contacted by the investigators and response rate was 44%. One person refused the invitation. Finally, 16 participants took part in the study (15 males, 1 female). Details of the participants are provided in Table 1. The age was in the range 22-63 years (mean 39.5, SD 14.5). Almost one-third of the sample reported a daily use of their motorcycle at the time of the tests. Despite the specific criterion for inclusion, three participants reported less than one ride per week, one of which was not an active rider at the time of the tests. Concerning the mileage, the majority of the participants declared between 1000 and 5000 km per year. Sports bikes were the most common type of motorcycles owned by the participants. The sample included a former police motorcyclist and a former professional motorcycle tour guide (both still riding daily their motorcycles at the time of the tests).

Table 1. Summary of the participant riders involved in the validation

Age	**n**	**%**	**Type of bike owned**	**n**	**%**	**km travelled per year**	**n**	**%**	**Frequency of riding**	**n**	**%**
21-30	6	37.50	adventure	2	12.50	<1,000	2	12.50	less than once a week	3	18.75
31-40	4	25.00	cruiser	2	12.50	1,000 - 5,000	6	37.50	once a week	4	25.00
41-50	2	12.50	off-road	2	12.50	5,000 - 10,000	3	18.75	2-3 times per week	3	18.75
>50	4	25.00	sports	5	31.25	10,000 - 15,000	3	18.75	4-6 times per week	1	6.25
unknown	0	0.00	sports tourer	1	6.25	15,000 - 20,000	1	6.25	daily	5	31.25
			standard	1	6.25	> 20,000	0	0.0	unknown		0.00
			touring	3	18.75	unknown	1	6.25			
			unknown	*0*	*0.0*						
Total	*16*	*100.00*		*16*	*100.00*		*16*	*100.0*		*16*	*100.00*

Procedure

Ethics approval for this study was granted by the Monash University Human Research Ethics Committee (project n. CF15/180 -2015000084). All participants received an explanatory statement with details of the study and provided informed consent.
Before using the simulator, participants filled in the ‘demographic and riding’ questionnaire collecting demographic data, riding attitudes, and opinions about motorcycle safety technologies.

Familiarisation phase. Before starting, participants were instructed on the counter-steer control strategy for lateral control of the simulator. Participants experienced the motorcycle rig and its controls in a country road environment, free from obstacles in the carriageway, in a speed range between 40 km/h and 80 km/h (see Figure 2). The initial rides consisted of two runs of 5 minutes each, with 2 minute break in between. A representation of the track used for the tests is plotted in Figure 3. Except for the first run participants wore helmet and gloves during all the tests runs.

Figure 2. Screenshot from the visual output of the simulator showing the road environment used for the tests.

Test phase A. Participants performed four runs of 2-3 minutes each, riding the motorcycle simulator along the same three-lane road setting used in the familiarisation phase, in absence of traffic. Each run included up to three large-radius curves (one every 40-60 s) and the road was almost flat. In the first three runs, participants were instructed to keep the vehicle centred in the middle lane, at the constant speed of respectively 60 km/h, 80 km/h, and 100 km/h. In the fourth run, participants were instructed to maintain the vehicle at a constant target speed, and to change lane in a given sequence when indicated by the researcher, at intervals of 20 seconds. At the end of each run, participants provided an evaluation of the handling of the simulator with respect of the given task (i.e. tracking speed and steering). Handling qualities were rated in a scale from 1 (excellent) to 10 (major deficiencies in the system) based on a rating scale procedure designed to evaluate the handling qualities of aircrafts. (The handling quality rating chart used in the tests is provided in the Appendix.). At the end of the set of runs, participants completed a questionnaire with closed-ended questions on the realism of the following riding conditions: (i) constant speed; (ii) braking and accelerating; (iii) steady cornering; and (iv) lane change manoeuvres. Participants were asked to rate on a 5-point Likert scale with ratings ranging from ‘strongly disagree’ to ‘strongly agree’ on a series of questions, for example, “While braking and accelerating, the perception of speed change was realistic.” The Likert scale was then converted into a scale from 0 (‘not realistic at all’) to 5 (‘highly realistic’). Additional questions addressed the response of the control inputs (namely, throttle, brake, and steering) with options ranging from ‘too little’ to ‘too much’.

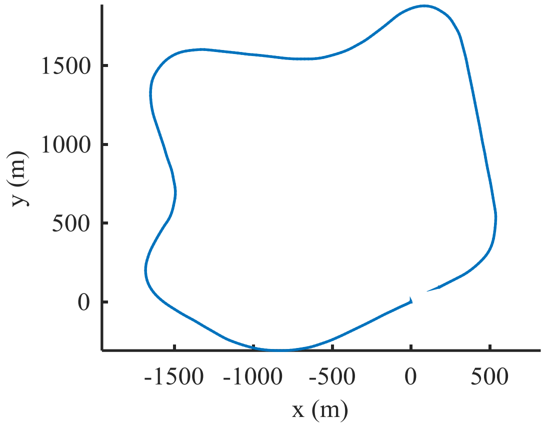
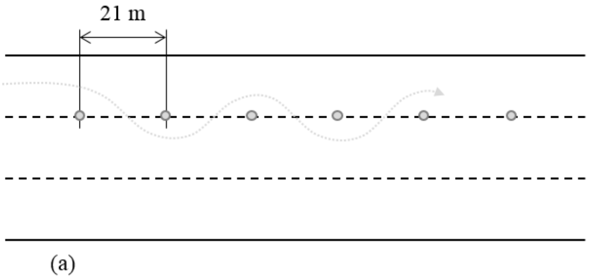


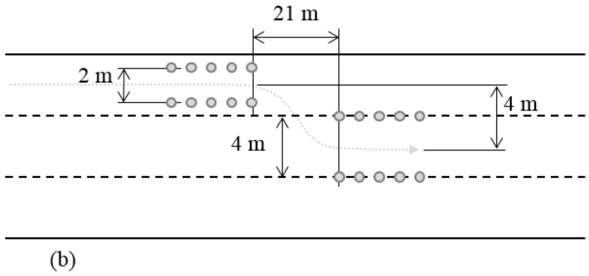
Figure 3. Representation of the test track adopted in phase A tests.

Test phase B. In this phase, participants performed slalom and lane change manoeuvres along a straight road. The former manoeuvre consisted in a slalom around street cones aligned at a distance of 21 m from each other (Figure 4a). The latter manoeuvre consisted in nominal lateral deviations of 4 m in a longitudinal distance of 21 m, operated passing through corridors of traffic cones, respectively 2 m and 4 m wide (Figure 4b). Participants performed sets of three runs of slalom and lane change at each one of the following speeds: (i) 40 km/h; (ii) 60 km/h; and (iii) 80 km/h. At the end of each set, participants evaluated the handling qualities of the simulator for the specific manoeuvre at the given speed. At the end of this phase B, participants completed a questionnaire addressing the realism of the simulator during the slalom and during the lane change manoeuvres.

At the end of the test session, participants provided their subjective evaluation in writing via open-ended questionnaire.



(a)



(b)

Figure 4. (a) Slalom test setting. (b) Lane change test setting.

Body lean strategy. Four participants participated in a first pilot group and did not perform phase B. Indeed, at the end of phase A, they were instructed to implement small lean movements of the body in the direction of the turn, in combination with the counter steer input. This will be indicated with the name of ‘body lean strategy’. The four participants then repeated the whole set of tests of phase A, and filled in again the evaluation forms.

For the remaining twelve participants, the body lean strategy was introduced during the warm-up phase as optional for the remainder of the tests. This second group of participants performed both phase A and phase B tests.

Data analysis

The simulator was programmed to record the following parameters of the motorcycle during the test: (i) Cartesian coordinates of the centre of gravity of the host vehicle in an absolute reference system; (ii) lateral displacement of the host vehicle in a reference system aligned with the road (natural coordinates); (iii) longitudinal speed of the host vehicle; (iv) handlebar rotation; and (v) throttle and brake control values. For the handlebar mechanism, linear regression of a static calibration was used to compute steering torque values based on steering angles. This approximation was considered acceptable for the scope of the present study, given the relatively low frequency of steer inputs operated by participants (main component of the steer torque lower than 1 Hz in the tested manoeuvres).

The objective analysis focused on the following manoeuvres: (i) steady state cornering; (ii) slalom; and (iii) lane change. For steady state cornering, steer torque actions applied by participants in correspondence of a 40 m arc of 200 m radius curve in the first three runs of phase A were considered. For slalom and lane change manoeuvres, successful attempts with the lowest steering torque values were identified for each participant in each test condition. For each selected run, mean speed (v_m) and peak to peak values of the steering torque (τ_{p-p}) were computed. Results from the simulator tests were then compared with real-world tests available in the literature and numerical simulations obtained with the software BikeSim, the latter used as a surrogate of real world data.

Concerning subjective data, descriptive statistics were supported with statistical tests performed using two-sample, unequal variances T-Student test.

Results

Sixteen and 12 participants completed respectively test phase A and B.

Objective data

Datasets from the tests of two participants (P06 and P13) were not available for the analysis due to an unexpected fault in the recording script.

Steady state cornering

The values of steering torque and the mean speed for each participant along the constant radius turn in phase A tests are presented in Table 2. As expected, the right hand side curve (clock wise heading rotation) was negotiated while applying a counter-clock wise steer torque (opposite to the heading rotation). Torque values ranged from 5.0 Nm to 6.7 Nm at the target speed of 60 km/h, and from 6.9 Nm to 10.0 Nm at the target speed of 100 km/h. Average torque values were typically higher at higher target speeds. The results were compared with steady state torque values computed with Bikesim (Table 3). Bikesim results were consistent with the values presented in the literature.[31] At 60 km/h, the torque measured in the simulator was higher than the values obtained with Bikesim. At 80 km/h and 100 km/h the torque values measured in the simulator were closer to those computed for a small sports bike, and consistent with those of a large touring bike.

Table 2. Mean speed and steady state steer torque values adopted by participants during phase A tests while negotiating a 200 m radius curve (single attempt at each one of the three target speeds).

Participant	Target speed: 60 km/h		Target speed: 80 km/h		Target speed: 100 km/h	
	Mean speed (km/h)	Mean steer torque (Nm)	Mean speed (km/h)	Mean steer torque (Nm)	Mean speed (km/h)	Mean steer torque (Nm)
P00	na	na	na	na	na	na
P01	58.3	5.0	76.4	6.6	95.3	7.0
P02	56.8	5.2	74.0	5.9	96.8	6.6
P03	60.7	5.7	78.4	6.9	100.4	9.7
P04	59.2	5.7	78.4	7.4	99.9	6.9
P05	60.8	5.2	78.4	5.0	99.0	8.2
P06	na	na	na	na	na	na
P07	63.8	5.6	82.6	6.0	100.8	9.8
P08	63.5	5.6	80.8	6.5	99.3	9.0
P09	61.1	5.7	81.3	7.4	95.3	8.8
P10	53.7	6.7	82.2	6.1	97.7	7.0
P11	58.4	5.1	79.7	6.5	101.0	7.1
P12	60.6	5.7	80.9	7.0	na	na
P13	na	na	na	na	na	na
P14	61.3	5.8	82.4	7.4	100.5	10.0
P15	60.9	6.1	78.0	7.2	99.5	8.8
Mean	59.9	5.6	79.5	6.6	98.8	8.2

Table 3. Steer torques computed with baseline motorcycle models in BikeSim.

Manoeuvre	200 m radius curve			Slalom	Lane change (lateral displacement 4 m)		
Target speed (km/h)	60	80	100	60	40	60	80
Steer torque type	Steady state τ (Nm)			Peak to peak τ_{p-p} (Nm)	Peak to peak τ_{p-p} (Nm)		
Big cruiser	1.1	1.7	2.3	81.9	7.5	20	32.9
Big touring motorcycle	3.2	4.4	5.8	88.9	10.6	25.7	42.5
Small sports motorcycle	2.9	5.2	8.1	71.5	8.2	17.6	29

Slalom manoeuvres

Results from a subset of the successful slalom manoeuvres performed in phase B tests are provided in Table 4. For each participant, we focused on the runs requiring the minimum effort to accomplish the task. The inter-participant variability in the τ_{p-p} was high. Even when restricting the analysis to the runs performed with a deviation from the target speed within the range ±10%, the maximum value was almost double the minimum value in all the three target speeds. However, the inter-participant mean values of τ_{p-p} were similar for the three target speeds, ranging from 30.4 Nm to 36.9 Nm respectively at 80 km/h and 60 km/h. A representative example of a slalom manoeuvre executed with the simulator is plotted in Figure 5. The magnitude and phase of the steer torque signal were compared with the results of the on road testing presented by Cossalter, Lot [32] (vehicle: Aprilia Mana 850; cone distance: 21 m; mean speed: 68.8 km/h; peak torque: 45.3 Nm; $\tau_{p\text{-}p}$ phase: 3.4 rad). The steer torque was applied approximately in phase-opposition both in the real motorcycle and in the simulator, but the peak torque measured in the real motorcycle was almost double the values measured in the simulator. BikeSim simulations were consistent with Cossalter's tests (see Table 3).

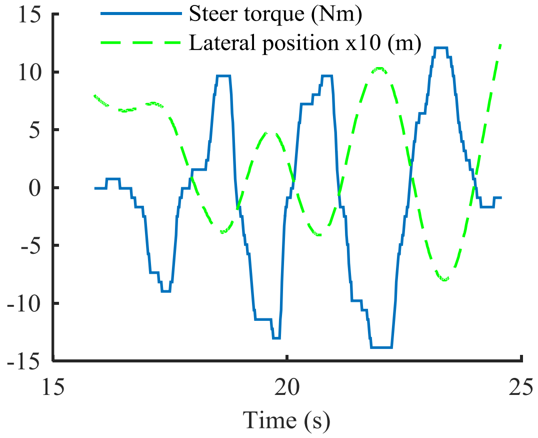


Figure 5. Participant P07 performing the slalom with target speed 60 km/h (mean speed 62.1 km/h).

Table 4. Mean speed and peak to peak steer torque values adopted by participants during the slalom tests in phase B.

Participant	Target speed: 40 km/h		Target speed: 60 km/h		Target speed: 80 km/h	
	v_m (km/h)	$\tau_{p\text{-}p}$ (Nm)	v_m (km/h)	$\tau_{p\text{-}p}$ (Nm)	v_m (km/h)	$\tau_{p\text{-}p}$ (Nm)
P00	na	na	na	na	na	na
P01	na	na	na	na	na	na
P02	na	na	na	na	na	na
P03	na	na	na	na	na	na
P04	40.1	35.6	61.4	49.3	86.9	45.3
P05	39.7	28.3	58.1	23.4	na	na
P06	na	na	na	na	na	na
P07	35.6	28.3	62.1	24.2	83.3	38.0
P08	52.2	53.4	53.2	46.1	na	na
P09	45.0	46.1	67.1	18.6	87.9	17.8
P10	41.6	25.9	57.6	31.5	76.8	27.5
P11	41.5	20.2	65.2	38.0	82.6	23.4
P12	44.6	27.5	68.0	38.0	82.7	20.2
P13	na	na	na	na	na	na
P14	40.0	32.3	60.9	28.3	82.4	44.5
P15	32.6	37.2	57.2	71.2	77.5	26.7
Mean	41.3	33.5	61.1	36.9	82.5	30.4

Lane change manoeuvres

Results from a subset of the successful lane change manoeuvres performed in phase B tests are provided in Table 5. Mean speed and peak to peak steer torque values adopted by participants during the lane change tests in phase BTable 5. For each participant, we focused on the runs requiring the minimum effort to accomplish the task. For this manoeuvre, the inter-participant variability was much smaller than for the slalom, and the mean values of $\tau_{p\text{-}p}$ were generally higher at higher speed. A representative example of a lane change manoeuvre executed with the simulator is plotted in Figure 6. Participant P07 performing a lane change with target speed 40 km/h (mean speed 37.9 km/h). In this manoeuvre, the delay between initial steering torque and initial lateral displacement was 0.26 s. Also for lane change, the magnitude and phase of the steer torque signal were compared with the results of the on road testing presented by Cossalter, Lot [32] (vehicle: Aprilia Mana 850; lateral displacement: 3 m; mean speed: 55.3 km/h; $\tau_{p\text{-}p}$: 84.0 Nm). Consistent with the slalom manoeuvre, the peak torque measured in the real motorcycle was higher than the typical values measured during the simulated manoeuvres. BikeSim simulations showed lower steer torque inputs needed to perform the lane change compared to the real motorcycle. BikeSim values obtained with the three vehicles at target speeds of 60 km/h and 80 km/h were consistent with the steering torque inputs measured in the simulator at the same speeds (see Table 3).

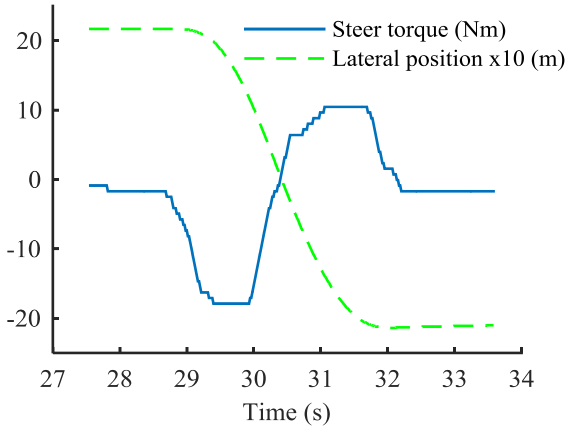


Figure 6. Participant P07 performing a lane change with target speed 40 km/h (mean speed 37.9 km/h).

Table 5. Mean speed and peak to peak steer torque values adopted by participants during the lane change tests in phase B.

Participant	Target speed: 40 km/h		Target speed: 60 km/h		Target speed: 80 km/h	
	v_m (km/h)	$\tau_{p\text{-}p}$ (Nm)	v_m (km/h)	$\tau_{p\text{-}p}$ (Nm)	v_m (km/h)	$\tau_{p\text{-}p}$ (Nm)
P00	na	na	na	na	na	na
P01	na	na	na	na	na	na
P02	na	na	na	na	na	na
P03	na	na	na	na	na	na
P04	36.1	29.1	62.0	36.4	75.6	43.7
P05	39.3	29.9	56.3	59.9	79.9	30.7
P06	na	na	na	na	na	na
P07	37.9	26.7	57.2	28.3	81.2	29.9
P08	40.1	27.5	59.4	45.3	80.4	57.4
P09	41.5	21.0	56.6	13.7	84.3	16.9
P10	45.2	14.5	64.2	19.4	79.0	22.6
P11	39.9	17.8	61.1	16.1	78.4	29.9
P12	42.5	21.8	68.8	27.5	88.2	40.4
P13	na	na	na	na	na	na
P14	42.6	20.2	59.9	22.6	80.0	29.9
P15	37.4	22.6	55.5	30.7	77.5	55.0

Mean	40.3	23.1	60.1	30.0	80.5	35.7

Subjective data

Body lean strategy

In the pilot study focusing on the body lean strategy, three out of four participants repeated phase A runs after introducing this strategy (one participant withdrew after phase A due to discomfort). The responses from this subset of participants, supported by handling ratings and questionnaire results, indicated that counter steer inputs can be more intuitive when also implementing the body lean strategy. Consequently, body lean strategy was introduced as optional during the warm-up phase for the following participants. Finally, all participants implemented this strategy during their tests.

Handling quality ratings

Participants rated phase A runs in the range from 1 (excellent) to 5 (moderately objectionable deficiencies), with overall mean value of 2.96 (standard deviation 0.87). In phase A (country road riding), the mean ratings were consistent across the speed range considered. When performing lane changes, the handling score in the same country road environment was poorer than the basic scenario without a lane change. In order to test the effects of adaptation to the simulator with respect to the handling perception, six participants repeated the final lane change test of phase A after completing phase B. The ratings for the lane change task in country road environment performed at the end of the test session were slightly lower (mean ratings at first and second attempt respectively 3.17 and 2.33). This suggested that the simulator achieved good levels of handling quality (ratings around 3) in short time, with slight improvement as participants got more used to it.

Concerning phase B, participants reported better handling during lane change manoeuvres than when completed the slalom task. In fact, the mean handling ratings for slalom and lane change were respectively 4.31 and 2.94 ($t(68)=3.74$, $p<0.001$). For the slalom, handling ratings were poorer at 80 km/h than at 40 km/h ($t(20)=2.96$, $p<0.005$).

Mean handling quality ratings provided by the subgroup of twelve participants are given in Table 6.

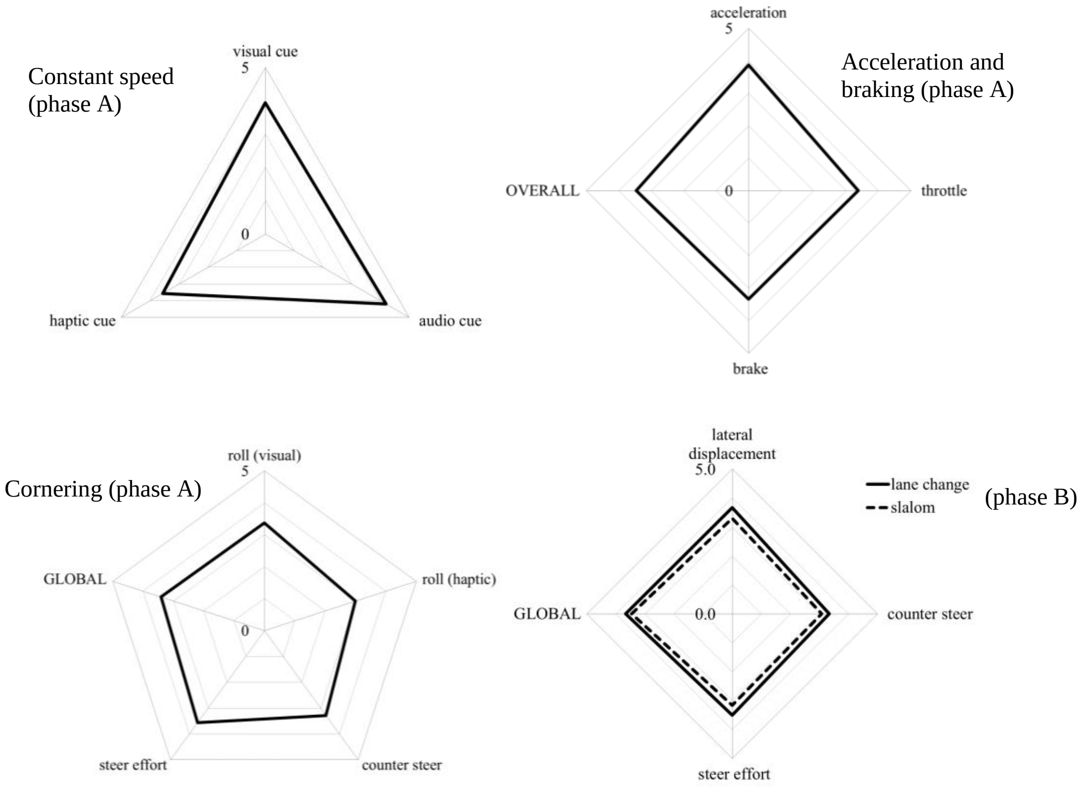
Table 6. Mean handling quality ratings in the different test sets in the range 1 (excellent) to 10 (major deficiencies in the system).

	Phase A		Phase B	
Target speed (km/h)	Country road	Country road, lane change	Slalom	Lane change
40			3.33 (1.23)	2.67 (1.07)
60	2.92 (0.80)		4.17 (1.27)	2.58 (1.00)
80	2.83 (0.83)	3.17 (0.94)	5.41 (1.88)	3.58 (1.83)
100	2.92 (0.90)			

(Standard deviation in brackets)

Questionnaires

The results of the questionnaires for the sixteen participants were synthesised in the form of radar-type graphs in Figure 7. This representation allowed for comparisons with previous studies, in particular with the reference validation study.[32]


Constant speed (phase A)

Acceleration and braking (phase A)

Cornering (phase A)

(phase B)

Figure 7. Mean scores for phase A and B tests in the range from 0 (‘not realistic at all’) to 5 (‘highly realistic’)

Open-ended questions addressed the following aspects: opinion about the simulator; opinion about the steering control; and likes/dislikes. Concerning the overall opinion, statements declaring general appreciation for the simulator and its high level of realism were frequent (respectively seven and six instances). Three participants also highlighted the high quality of the visual cues. Four statements indicated an initial discomfort with the steer control and four participants declared that steering was counter-intuitive or not completely realistic during the tests. Five statements expressed negative opinion about the motion cues (not enough or not well correlated with the steering). When asked directly about the steering control, two participants also indicated that it was difficult to get used to the steering input. A number of specific deficiencies of the steering input were reported: too much or not enough sensitive (respectively two and three statements), and slow in its response (two statements). Four statements highlighted the fact that the steering control became natural after some practice, and in seven instances, participants expressed good appreciation for the steering system. Participants liked the realism of the simulator, the visual and auditory cues, the vibration cues, the motion cues during longitudinal accelerations, and the fact that a real bike was used for the rig. Participants disliked the roll cues, the pitch cues, the throttle response, and the steering response at low speeds. Only one participant expressed explicit dislike for the counter steer approach adopted in the simulator. None of the participants expressed negative opinions about the non-tilting horizon in the visual cues. Two participants noticed that the dynamical behaviour of the bike resembled a passenger car while negotiating a curve, due to the speed reduction produced by the turning manoeuvre. A synthesis of the responses is provided in Table 7.

Table 7. Synthesis of the responses provided by participants in the open-ended questions.

	Positive opinions		Negative opinions	
Question	Statements	Frequency N.	Statements	Frequency N.
Overall opinion	Good/very good/excellent	7	Disconcerting at start	4
	Realistic	6	Counter intuitive/unrealistic steering	4
	Good visual cues	3	Not enough physical lean	3
	Controllable	2	Slow steer response	2
			Behaves like a car	2
			Not enough pitch	1
			Motion cues are confusing	1
			Throttle response	1
Steering control	Quite good/good/very good steering	7	Sensitiveness: Too much/not enough	5
	User was able to adapt to steering	4	Not enough physical lean	3
	Realistic	1	Counter intuitive/weird	3
	Intuitive	1	Disconcerting at start	3
			Difficult to adapt	2
			Slow response	2
			A little demanding	1
			Too soft feedback	1
Likes/Dislikes	Realism	5	Motion cues were confusing	3
	Auditory cues	5	Not enough pitch cues	3
	Visual cues	5	Brakes	3
	Pitch cues while braking/accelerating	4	Difficult to maintain target speed	4
	Vibrations	4	Weird turning behaviour at low speeds	2
	Real motorcycle rig	3	Not enough lean cues	2
	Brakes	1	Slow steer response	2
	Speed sensation	1	Too much lean cues	1
			Poor visual textures	1
			Counter steer	1

Discussion

The aim of this study was to validate a low-cost motorcycle simulator that implemented a counter steering input strategy with realistic feedback on the handlebar, obtained via simple elastic mechanism. This low-cost upgrade of an existing simulator was designed to investigate realistic steering inputs of the rider for the purposes of the development of rider assistance systems such as MAEB.

The validation process presented in this paper produced encouraging results both from objective and subjective viewpoints. Considering the objective validation in standard manoeuvres, general agreement was found between steering inputs applied in the simulator and those applied in reference tests involving real and simulated motorcycles.

In steady state cornering, the magnitude of steering torques was generally higher in the simulator. However, the sign of the inputs and the trend with speed variations were consistent with riding a real motorcycle. It is worth noticing that realism of steady state cornering in country road setting is important for the scopes of the simulator. In fact, an essential condition for investigating steering reactions of the rider in unexpected, critical events is that participants are subjected to a realistic virtual ride in normal conditions involving steer inputs – such as negotiating curves in a country road environment.

Slalom and lane change tests were challenging for participants, in particular at higher speed, particularly because of the absence of a specific warm-up session for these manoeuvres. However, the best attempt was often achieved in the first run (30% of the tests in phase B). This is particularly interesting in the perspective of investigating the rider behaviour when facing unexpected events.

Concerning the slalom, it is worth noting that driving simulator studies typically avoid rapid and repeated cornering to avoid motion sickness. In our tests, despite the fact that the steer input magnitudes were not always as large as real world data, shape, signs, and phase of the inputs were consistent with real riding. It is common for results in the simulator to follow the same trend as the real world, but to have a different magnitude.[33]

Lane change is highly relevant for the development of assistance systems that operate vehicle control actions in the pre-crash phase (such as MAEB, which applies autonomous braking) that may interfere with the rider's steer inputs. In fact, this type of manoeuver can be considered an approximation of an emergency lateral avoidance manoeuvre; see for example Giovannini, Savino [34]. Results from the experiments indicated an overall consistency between the inputs (shape, sings, and phase) for lane change recorded in the simulator, those measured in real world data and those simulated with detailed motorcycle models, despite the magnitude of the steering torque inputs seen in the simulator were lower than real world data. Given the fact that the proposed simulator aimed to reproduce steering inputs in lateral avoidance manoeuvres, discrepancies in the steering torque magnitude are critical. This problem can be addressed by tuning the stiffness of the steering springs. The tuning process should optimise the performance of the simulator to best reproduce steering inputs during lane change manoeuvres in the desired speed range and for the desired type of vehicle.

Regarding the subjective assessment, ratings provided by participants indicated good handling qualities and realism of the simulator in country road setting (phase A). As noted already, this aspect is important to allow participants immerse in the virtual environment prior to presenting unexpected events, in the perspective of investigating emergency reactions. Participants also reported good handling for the slalom and the lane change tests. Furthermore, results suggested that these handling properties were achieved quickly. Concerning realism, the overall results of the subjective evaluation were comparable with those of more sophisticated and complex simulators presented in the literature.[32] Responses to the open-ended questions highlighted the good level of visual and auditory realism. These aspects play an important role as they contribute in the process of adaptation to the simulated environment. Some participants' responses also indicated that counter-steering was occasionally perceived as counter-intuitive, confirming the results of previous studies.[27] This must be taken into account when designing future experiments with the simulator.

Finally, further investigations could try to clarify the contribution of what we called "body lean strategy", which in our study seemed to improve the perceived realism of our simple motorcycle simulators.

Limitations

This validation study focused on medium-high speeds. At speeds lower than 40 km/h, the behaviour of the passenger car model used in the physical engine of the simulator deviates remarkably from a motorcycle model. The present setup is expected to achieve poor levels of realism at lower speeds. Simulating a motorcycle at low speed is particularly challenging even when using a detailed motorcycle model, as shown in previous studies.[35] Other studies recommended avoiding counter-steer strategies at low speeds.[27] Considering that MAEB is relevant typically from 30 km/h,[36] further consideration should be given to identify low-cost options for low-speed, realistic riding simulations.

Conclusions

This paper presented a low cost motorcycle rig for a riding simulator based on a pre-existing car driver simulator. The validation process of this new motorcycle simulator involved 16 participants. Quantitative results concerning the steering inputs while testing steady state cornering manoeuvres (radius 200 m) were seen realistic in the speed range from 60 km/h to 100 km/h. Lane change manoeuvres were tested in the speed range from 40 km/h to 80 km/h. The results of the tests showed that the steering torques applied by participants were consistent in both magnitude and phase with the results of computer simulations based on detailed motorcycle models. The subjective assessments revealed that the low-cost motorcycle simulator was able to achieve a level of realism that is comparable with much more sophisticated solutions, despite the fact that the vehicle dynamics was based on a passenger car model. Specifically, the proposed steering assembly equipped with elastic resistance and combined with implementation of a counter-steer strategy was found satisfactory by most of the participants. Recommending the riders to lean their body while steering was found to be a simple way to improve steering realism. Concerning the possibility to use the real time car model instead of a motorcycle model in the simulator, results were encouraging: only two participants noticed some resemblance with a car behaviour. In particular, that was not due to the response of the steering control, but rather to the tendency of the simulated vehicle to slow down while negotiating curves. In conclusion, this low-cost simulator was proved able to investigate realistic motorcycle steer inputs in lateral avoidance scenarios at medium-high speeds. This result is meaningful in showing a practical and affordable way to create new riding simulators for specific test scenarios, thus potentially fostering the research of human factors in the motorcycle domain. In order to fully validate the use of this simulator as a tool for the development of rider assistance system, further work should investigate also the realism of participants’ reactions when simulating unexpected, emergency situations.

Acknowledgements

The research leading to these results has received funding from the European Union Seventh Framework Programme FP7/2007-2013 under grant agreement n. 328067 (ABRAM project). The authors acknowledge Mr Nebojsa Tomasevic for his technical support.

The authors also acknowledge the Monash Injury Research Institute, Monash University, for providing funding and equipment.

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Appendix

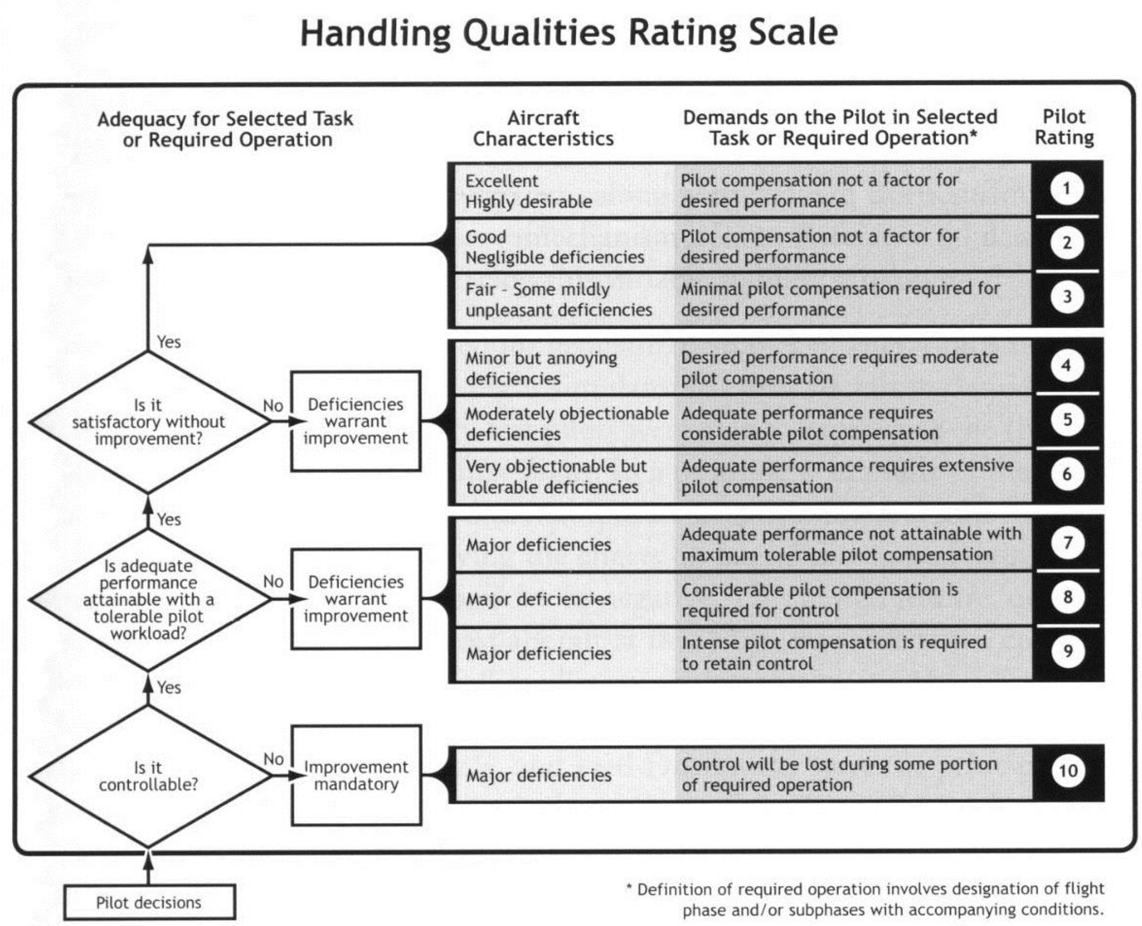

Figure 8. Handling qualities rating scale