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RESEARCH AND IMPLEMENTATION OF MOTORCYCLE SIMULATOR CONTROLS

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Abstract. The paper is focused on research in the field of motorcycle simulator controls from the rider's point of view, with a focus on the longitudinal and lateral dynamics of vehicle. The subject of the research is the design and testing of a suitable composition of input signals controlled by the rider and their integration into the virtual scene. The design and testing of the communication interface between the HW simulator and the physical model of the motorcycle is mentioned in the paper as well. Furthermore, the work describes the suitable HMI elements of the motorcycle and their integration options into the simulator system. In conclusion of the article, various variants, and approaches for controlling the developed motorcycle simulator are discussed, including the possibilities of validating the achieved results.

Keywords: Motorcycle simulator, motorcycle roll, rider performance, simulator control approaches.

1. Introduction

Powered Two Wheelers (PTW) riders are an inherent part of transportation system. PTW users are also vulnerable road users. Specific group of PTW riders are motorcycle riders. Focusing on usage of motorcycle we largely observe transport and recreation. Motorcycle is often purchased based on excitement and enjoyment [1]. These factors affect challenges associated with PTW safety. It means other road users, road environment, vehicles and PTW users itself [2]. Motorcycle riding popularity grows and together with this trend grows the importance of motorcycle riders' behaviour research because the human factor plays big role in motorcycle crashes [3]. In the Czech Republic environment, the Yearbook of road accidents in the Czech Republic 2020 published by Police of the Czech Republic presents that despite the total representation of accidents caused by motorcycles of 2,1 % accidents result in 10,2 % of total fatalities. Data from [4] shows human factor errors in case of accidents containing motorcycle rider. From the point of view of rider, we observe the highest number of identification errors (e.g., incorrect evaluation of the route and thus not adjusting the driving speed). The most endangered group of riders according to absolute number of fatalities are riders 25–44 years, but relatively the group of riders 15–17 years. Motorcycle riders are trained in the similar way as personal car drivers. It means that riders start the training in the driving school. Specific feature of the rider trainings is differentiation of more than one group of riding licences than e.g., one group up to 3,5 tons in case of driving licence. This fact causes that riders start the training more than once during lifetime – to achieve higher group of riding licence and thus to be eligible to ride more powerful motorcycles. It brings an opportunity to extend and deepen the training. Focusing on safety manoeuvres, that trained rider should know and handle, the rider must practise in the way to translate them into long-term as well as procedural memory [5]. In hazard situations we observe that advanced trained riders react faster in hazard situations than only experienced riders [6]. The differences are also seen in motorcycle simulator study. Riders performed left and right-hand bends and the novice riders tend to take bad position in lane more than inappropriate speed [7]. The study also shows that riding skills are also significantly documented in laboratory conditions. Driving simulators are an inherent part of automotive research [8] as well as part of the training in driving schools [9, 10], moreover according to the driving schools' teachers see driving simulator as part of intense long-term training for young riders to reduce their hazard behaviour [11]. Motorcycle simulators in terms of riders training have also the same potential as car driving simulator. It means training of preventive safety of riders [12]. Designing a motorcycle simulator, it is important to define target levels of physical (hardware and physical feedback for rider etc.) and functional (engine, virtual reality, visualisation etc.) fidelity that appear that have major impact on simulator validity. In this way investments into the simulator are better spent on simulator engine and visual databases than into the hardware in terms of physical fidelity [13]. Physical fidelity of course could increase riders' sense of presence and thus increase simulator validity [14] but physical fidelity improvements are accompanied with large cost investments and only small quality of data increases. Sufficient functional fidelity leads to good quality of obtained data despite lower levels of physical fidelity [13]. The riding of a PTW vehicle is much different from driving a car. The main difference comes from the principle of PTW, which are spontaneously unstable. This property significantly affects longitudinal and lateral dynamics behaviour as well as command and control of the vehicle [15]. The manoeuvrability of the real motorcycle is realized especially by the movements of the rider [16]. These facts are used in all the concepts and must be taken into account when designing the motorcycle simulator. The main difference between control approaches is how inputs from the rider are detected. The most advanced PTW simulators have a system that allows control by human-body feedback. This concept requires a cueing platform with multiple DOFs and a complex control system that can provides a realistic response. More common motorcycle simulators have sensors placed on mock-up in such a way that they can detect the movement of the rider indirectly; examples are sensors implemented in footrests, steering sensors, and sensors that allow roll detection. In addition to movement sensors, it is necessary to track, record and evaluate command inputs from the rider side (throttle and brake lever position, clutch, shifted gear, etc.) [17]. Based on data acquisition and evaluation, movement of these simulator concepts are controlled by algorithms and filters which aim to recreate riding accelerations and angular velocities by using actuators (servomotors, etc.) [18]. Simulators are proved to be the experimental tool for testing of HMI (Human Machine Interface) features. HMI elements could be easily designed and implemented into the virtual scene using VR (Virtual Reality) glasses [19]. According to the hardware setup we recognize reduced motion, parallel platform, and serial platform motorcycle simulators. Even the reduced motion simulator is proved tool for assessing riders training, hazard perception and mental workload. On the other movable platform simulators bring benefits when assessing scenarios including motorcycle counter-steering and transition phase between slow and high speed [17]. In case of motorcycle simulator without motion platforms the challenge is the appropriate setup of handling inputs, visualisation, and engine behaviour to reproduce the optimal riding experience. This is the challenge that the rest of the paper focus on.

2. Method

In the experimental phase, we focus on research of an appropriate approach for handling inputs of motion-reduced simulator. The goal is to find a method to mediate an experience like the rolling performance of the motorcycle, even in the case of a static simulator platform. In this way, we propose specific inputs in several combinations together with hardware adjustment in from rollable handlebars and VR glasses visualisation. The proposed variants are to be tested in a gymkhana scenario and compared with the results from the real test track.

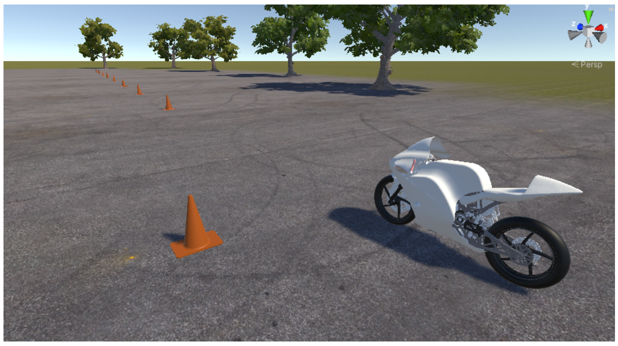

Figure 1. Virtual scene.

2.1. Simulator SW and HW

Our motorcycle simulator is being developed in Unity software (see Figure 1). This article follows on the research made in [20], where the SW simulator approach and architecture are described, as well as the simulated motorcycle parameters and category. In this paper, we focus on implementation of the lateral part of the physical model. In this way, we implemented three variants of steering possibilities. The simulator SW calculates the final angle of steering based on handlebar rotation, roll, and forces applied on footrests. The input signals enter the lateral part of the physical model, where they are combined and mutually weighted according to the weight curves. The whole virtual reality scene is visualised to the subject rider in the VR (Virtual Reality) glasses.

The simulator hardware consists of the motorcycle and handlebar body that are controlled by the rider wearing VR glasses (see Figures 2 and 3). The handlebars are attached to the motorcycle body by a ball joint that allows rolling around the motorcycle longitudinal axis and steering rotation. The rider can steer the motorcycle in virtual environment by the actual roll of the handlebar body (due to inclinometer sensor), handlebar rotation (due to rotation sensor) and by weight transfer that is read on footrests (due to weight sensors). The rotation sensor is integrated into turn servo and thus provides spring and damping resistance of the steering.

2.2. Simulator experiment

The aim of the article is to examine different control approaches for the developed PTW simulator, while is focused mainly on rider inputs which affect lateral dynamics. Longitudinal dynamics in the context of a PTW simulator was investigated within the paper [20]. To objectively assess the approaches, an experiment was carried out with a total of three simulation cornering controls. During each session, the following data output from the virtual scene was collected: time, position (x,y,z), speed, virtual motorcycle roll, virtual steering angle. The data channels regarding rider inputs that were measured and recorded during the experiment presents Table 1. Measured channels varies for each scenario.

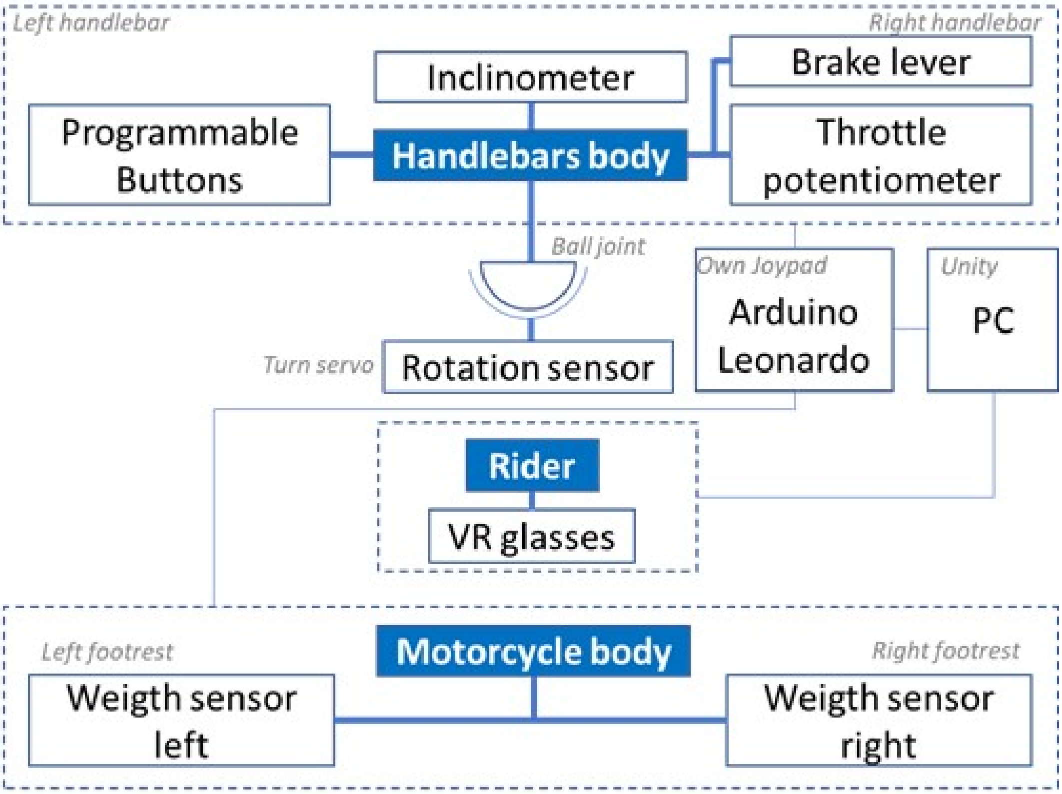

Figure 2. Simulator hardware block schema.

Rider inputs	Sc. 1	Sc. 2	Sc. 3
Throttle position	✓	✓	✓
Brake level position	✓	✓	✓
HMD roll	✓	✓	✓
Roll of the handlebars	✓	✓	✓
Footrests weight sensors	✗	✓	✓
Steering angle	✗	✗	✓

Table 1. Rider inputs scenarios.

The experiment took the form of a virtual track test in which the slalom (see Figure 4) was used as a representative of the typical manoeuvre to prove and test the handling characteristic of the motorcycle. Before the start of each scenario season, the probands were instructed about the control behaviour, and they have enough time for free practice. Then during the experimental phase, participants have three attempts to pass the slalom as clean as possible. After the tests performed, we ask riders for their subjective impression of each variant of the control behaviour.

In the first scenario, cornering was realized only based on roll of the handlebars around the longitudinal axis. For the second scenario, footrests weight sensors were added. In this scenario the simulation SW used two cornering inputs. In the third scenario we moreover added input from the turn servo with rotation sensor. The third scenario was carried out with fully equipped simulator so there were three rider's inputs which affect the roll and steering of the virtual model.

Figure 3. Simulator hardware – testing subject while riding.

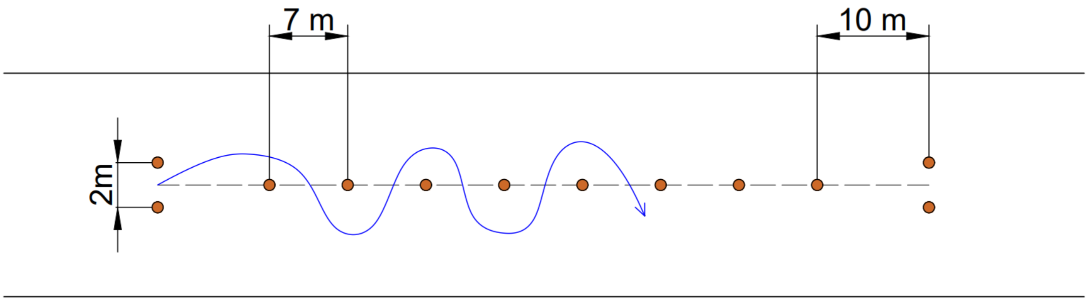

FIGURE 4. Setup of the track test – position of the cones.

FIGURE 5. Track test experiment layout.

2.3. Real test track

In order to compare and validate data measured on the simulator sessions, the real track test was performed in the same set-up (see Figure 5). The used motorcycle has the same performance and weight characteristics as we implemented in the virtual physical model of the simulator. Data were obtained using the developed data acquisition system [21] supported by the commercial measurement unit X-Sense MTI-G-710-2A8G4.

2.4. Testing hypotheses

To evaluate designed motorcycle control concepts, the following hypotheses was established:

- H1: Control concepts (Scenarios 1–3) do not affect the riding style while riding:
  - ▷ H1a: Rider's movements in terms of handlebar and head roll activity.
  - ▷ H1b: Rider's steering performance.
  - ▷ H1c: Rider's weight transfer.
- H2: Lateral dynamics data acquired while simulator experiment will not correspond with racetrack rides.

3. Results

3.1. Simulator scenarios

The following subsection focuses on the results across scenarios 1–3. It mainly aims to improve the riding style of the rider during the simulator session. Figure 6 presents the average phase shift between the HMD (Head Mounted Display) roll, the footrest weight ratio, and the motorcycle roll. The HMD roll represents the actual roll of the head of the rider. Footrests weight ratio acquire values from 0 to 1, when 0.5 means balanced situation – the same force applied both on left and right footrest. Phase shifts are compared according to the motorcycle roll that represents the x-axis. The HMD roll phase shift is calculated as the HMD roll peak position minus the motorcycle roll peak position. The footrest weight ratio shift is calculated in the same way. The shift was examined while cornering around cones. In this way, we examined 8 turns. In general, we see a trend that maximum weight applied on the footrest while cornering precedes motorcycle roll peak. The HMD roll, on the other hand, slightly follows the motorcycle roll peak. Concerning average values across scenarios 1 to 3 the weight ratio shift equals -2.7 m, -3.5 m, -2.3 m and the HMD roll shift equals 0.8 m, 2.0 m, -0.1 m. We observe differences between the scenarios. In the second the shifts reach the highest values across examined variants. Comparing Scenarios 1 and 3, we observe similar results. In the case of Scenario 3 we see the smallest shifts. The further differences of the first and third scenario examine Figure 7.

The graphs presented in Figure 7 provide a detailed comparison of the motorcycle roll and the steering angle within Scenario 1 and 3. All data were plotted as a function of distance from the start gate to the last cones that form the final gate. The distance shift could be observed (the most for participant 2), which could cause the choosing a different trajectory within rides. For participant 1 we observe significantly lower absolute values of the motorcycle roll and the steering angle. The total driving distance suggests about the riding style of this person which was diametrically different from the other probands.

3.2. Simulator versus Racetrack

The results of the roll characteristics during the slalom performed in the simulator and during the track test are provided in Table 2. All values were calculated as a mean of the three rides per participant and then the

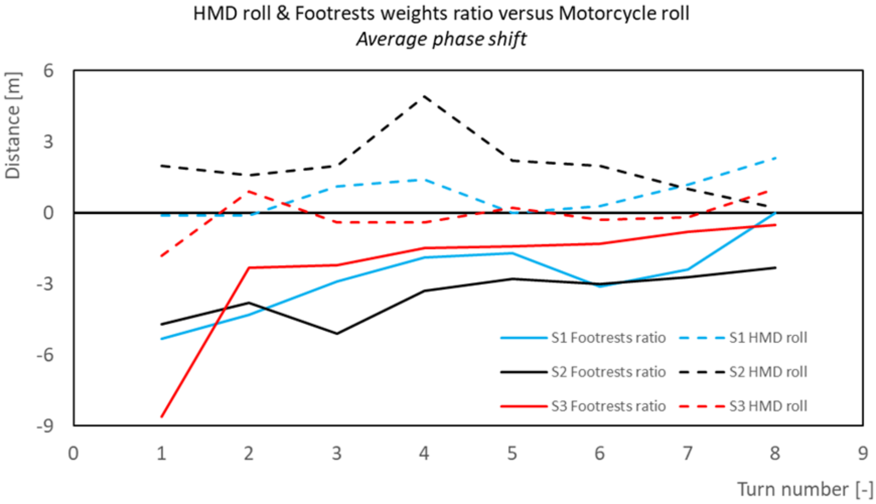

Figure 6. HMD roll and footrests weight ratio shifts from motorcycle roll.

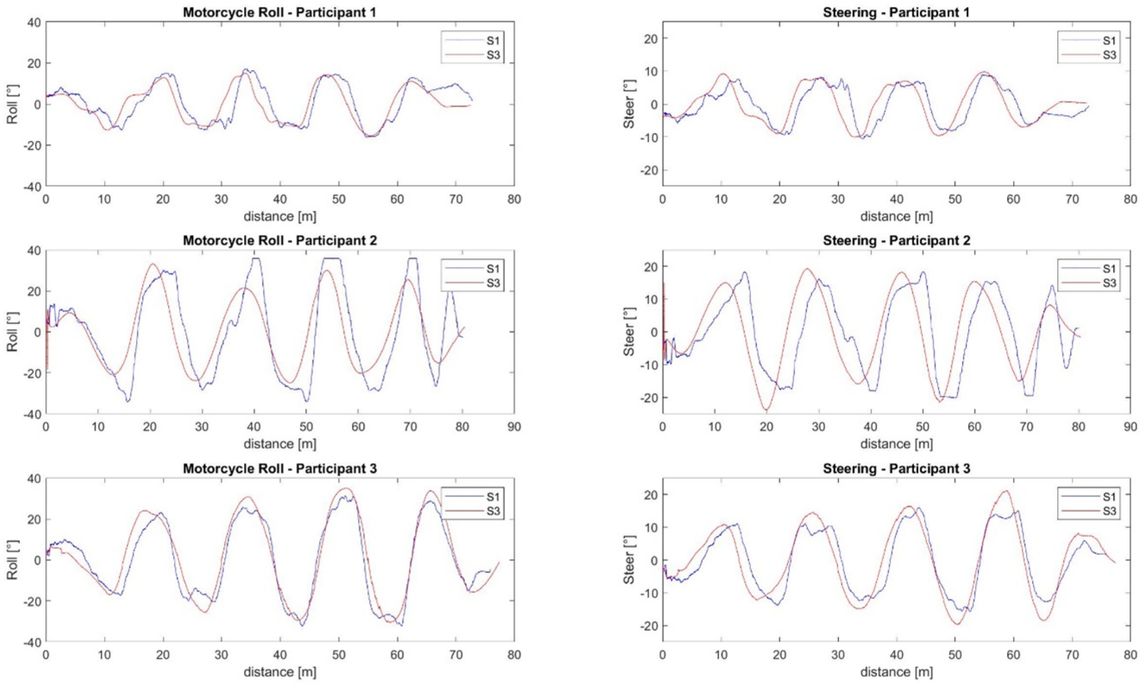

Figure 7. Detailed comparison of the motorcycle roll and the steering angle within Scenario 1 and 3.

Variables	**Racetrack ride**					
Subjects:	**Slalom T** [s]	**Roll Rate peak** [$° s^{-1}$]	**Roll right** [°]	**Roll left** [°]	**Roll Rate** [$° s^{-1}$]	**Time t** [s]
P01	2.26	68.20	11.10	13.33	28.88	13.15
P02	1.72	96.28	11.90	14.80	34.79	11.43
P03	1.91	69.21	8.41	11.13	25.21	12.17
average	1.96	77.90	10.47	13.09	29.63	12.25
percentage	100	100	100	100	100	100
Variables	**Simulator ride**					
Subjects:	**Slalom T** [s]	**Roll Rate peak** [$° s^{-1}$]	**Roll right** [°]	**Roll left** [°]	**Roll Rate** [$° s^{-1}$]	**Time t** [s]
P01	2.26	58.69	10.39	13.83	30.74	14.79
P02	2.08	101.20	10.49	15.24	37.25	13.11
P03	2.68	51.65	6.17	8.00	15.90	13.46
average	2.34	70.51	9.02	12.36	27.96	13.79
percentage	119	91	86	94	94	113

Table 2. Simulator versus racetrack comparison.

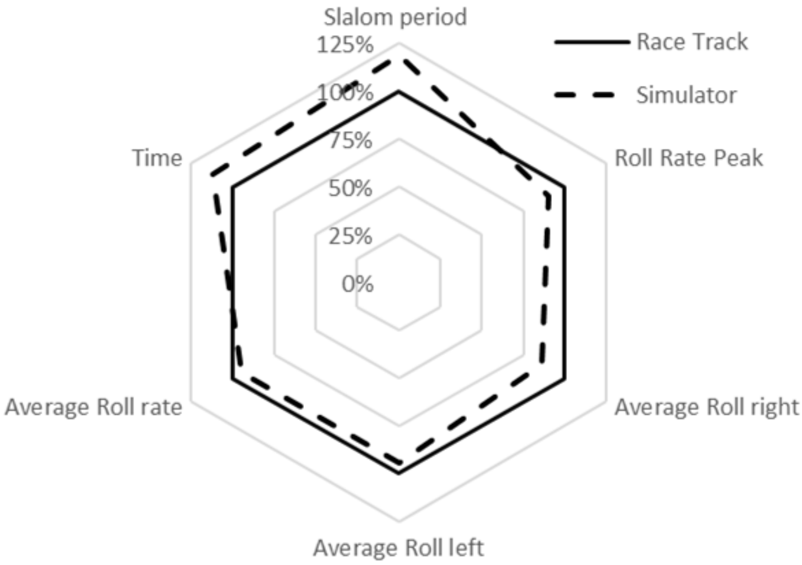

FIGURE 8. Racetrack versus simulator rides average values comparison.

average value was determined. The track test average values were then used as a basis for the comparison with simulator data. To be able to monitor the change rate of the motorcycle roll, the roll rate value [$^\circ\,s^{-1}$] was used. The values in column Slalom Period defines the mean of the time intervals between the repetition of the slalom wave.

Figure 8 presents a trade-off of simulator and racetrack rides. It means a comparison of the average values as stated in Table 2. In the figure, the racetrack results represent 100 %. When comparing racetrack and simulator rides, we observe similar results of roll and roll rate values. Regarding time, the simulator rides were generally slower, and the slalom period was longer.

4. Discussion

In this chapter, we describe the findings based on performed experiment and presented data. The resulting discussion is divided into two sections in compliance with stated hypotheses.

4.1. H1: The control concepts (Scenarios 1–3) do not affect the riding style while riding

In the first part of results in Section 3.1 we focus on rider style from the point of view of head and body movements. In this way Figure 6 shows that across tested concepts we observe their influence on synchronization of head and body movements. In the second scenario when the weight sensors as input controller were combined only with actual roll of handlebars, it caused non-negligible shift of forces applied on footrests peak shifts. Moreover, it affected the roll of the riders' head. From this point of view, as well as subject comments, the second scenario handling concept entailed a negative effect on natural riding style. In case of Scenarios 1 and 3 we observe similar resulting riding styles. Based on the riders' experience of the testing riders, we evaluated the third scenario as more appropriate. The first scenario was subjectively rated more sensitive. This assumption is assessed in detail in Figure 7. Analysing motorcycle roll within first scenario ride we observe bumpy curves in areas of cornering. This negative influence on riding style could be caused by an inappropriate perception of the actual roll angle and roll rate. This is also consistent with riders' subjective assessment. In the third scenario, we see smooth roll curves while cornering across tested subjects – even independently on absolute values belonging personal riding styles of testing riders. In the case of steering, we observe a similar effect on the steering angle as on the rolling angle. The interesting finding is that the riders performed a similar steering angle in scenario 1 knowing that the steering input is not active. Riders naturally steer the handlebars, even while focusing only on rolling the handlebar. The shifts between scenarios one and three in Figure 7 are caused by minor differences in the final trajectories. In the third scenario, the riders synchronized their movements the most among the concepts tested.

4.2. H2: Lateral dynamics data acquired while simulator experiment will not correspond with racetrack rides

Based on the results of the simulator and racetrack comparison, we observe differences in the duration of the slalom ride and the associated slalom period, where the total time spent is higher in simulator rides. This fact could be related to the different perception of velocity during simulator rides, which was also confirmed by the subjective impressions of participants 1 and 2. Although precautions were taken to ensure better perception of virtual vehicle speed, it will be necessary to improve some parts of the virtual physical model in the future, especially the sound module. Furthermore, the results focus mainly on the performance of the rider when cornering. Here, it is possible to observe slight nuances between the roll angle on the right and left during both the simulator and the track test rides. This phenomenon is common when riding a motorcycle, and most riders have lower values of roll angle on the right turns. However, the analysis performed showed that this effect is greater while riding a simulator. Another finding is that average simulator ride roll rate values reach up 94 % of racetrack rider. Similar trend is observed from the point of view of roll rate peak values, where simulator ride reaches 91 % compared to racetrack ride even though the only movable part of simulator were the movable handlebars allowing rolling and steering.

5. Conclusion

Motorcycle riders are common and moreover vulnerable road users. An important factor in motorcycle road accidents is human error, which strongly affects novice riders. Motorcycle training is often multistage, and thus riders applying for higher level of riding license visit training courses multiple times per lifetime. Long-term memory and repetition of traffic situations, as well as drilling of rider behaviour, could have a positive effect on road safety in general. In this way motorcycle simulators are one of the tools to achieve this goal. In addition, riding simulators are tools for HMI motorcycle research. In terms of simulator design, the good quality of the data collected is influenced more by functional fidelity than physical fidelity. The reproduction of credible riding experience is very important in the case of the vehicle simulator. In the paper, we analyse the possibilities of reduced motion simulator emendations. In the experiment preparation phased the simulator was equipped with movable handlebar body and footrests weight sensors that are typical rather among movable simulators. The experiment conducted contains an evaluation of three input control scenarios. The results of the simulator study were subsequently compared with the racetrack data. The limitation of the study is the lower number of subjects and the layout of the tracks. Data show that combination of handlebar rolls and steering sensor in combination with weight sensors could reproduce similar behaviour in terms of lateral dynamics parameters. Moreover, results show more smooth performed riding styles performed within tested scenario 3. This approach allows riders to move and perform weight transferring as they are used to while riding a motorcycle on the road. The proposed controls variant represented by scenario 3 in the simulator experiment phase will be furthermore analysed by a higher number of participants and in multiple dynamic riding scenarios. Acquired experimental results will be used for the further development of our motorcycle simulator.

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