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Objective and subjective evaluation of an advanced motorcycle riding simulator

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ABSTRACT

This paper outlines the characteristics of a top-of-the range motorcycle simulator and focuses on its objective and subjective evaluation. The simulator has been designed and built at the University of Padua over a the last years; it consists of a motorcycle mock-up with functional throttle, brakes, clutch and gearlever mounted on a five 'degrees of freedom' platform, a real-time multibody model of the motorcycle and an audio and visual systems. The purposes of the simulator are to test devices such as ABS, traction control and other ARAS in a controlled, safe environment, to study riders' behaviour and to train them. In order to be able to apply the results obtained on the simulator to the real world, an innovative procedure for the objective and subjective validation of motorcycle simulators has been developed and applied to the simulator in question.

Keywords: motorcycle, powered two wheelers (PTWs), simulator, safety.

1 INTRODUCTION

Nowadays, powered two-wheeler vehicles (PTW) are widely used not only for pleasure, but also for increasing mobility in the crowded urban and sub-urban roads of many European towns. For several reasons, PTW dynamics and safety have not been investigated as much as with four-wheeled vehicles, despite the fact that riders are among the most vulnerable road users. Therefore the development of devices aimed at improving the comfort and safety of PTWs, as well as investigating the behavioural factors that contribute to crashes, are important areas for research. Moreover, the roll degree of freedom which makes PTWs quick and prompt on urban roads and diverting on the rural track has some safety implications which require new riders to receive proper training. Unfortunately it is not easy to train new riders in dangerous situations, such as riding on a slippery road or emergency braking. From this point of view riding simulators may help both as a training tool and in the development of innovative devices aimed at improving rider safety.

It is worth noting that motorcycle riding simulators are not as widespread as aircraft and car driving simulators, and therefore the current selection is not very rich. Honda started to develop a series of motorcycle simulators in 1988; its first prototype consisted of a 5 DOF mock-up (lateral, yaw, roll, pitch and steer motions on a swinging system for the longitudinal acceleration restitution) and was based on a linear 4 DOF motorcycle dynamics model. In 1996, as a consequence of the change of the Japanese Road Traffic Act which required the use of simulators in riding schools lessons, Honda put a mass-produced model on the market. This second prototype had a simplified 3 DOF mock-up (roll, pitch and steer motions) and it was based on a properly tuned empirical motorcycle model. In 2002, Honda developed a third prototype which consisted of a 6 DOF plan manipulator for the mock-up motion, a head mounted display for visual projection, a 4 DOF model for the lateral motorcycle dynamics and a 1 DOF model for the longitudinal dynamics [1], [2]. The Department of Innovation in Mechanics and Management (DIMEG) of Padua University began the development of a riding simulator in 2000 and presented the first prototype in 2003 [3]. In 2003, PERCRO laboratory also presented its riding simulator with a real scooter mock-up mounted on a steward platform [4], and in 2007 INRETS presented a riding simulator based on a 5 DOF platform and a linear 5 DOF motorcycle mathematical model [5].

The DIMEG motorcycle simulator has been developed to test devices such as ABS, traction control and other ARAS in a controlled, safe environment, to study riders' behaviour and to train them. It is possible to reproduce and consequently analyse the most critical and risky situations that a normal rider will find every day on all roads. However, in order to apply the results obtained by the studies on the riding simulator to a real motorcycle it is necessary that the behaviour of both simulator and motorcycle are the same. Since there are very few studies focussing on motorcycle simulators and in particular on their validation, this paper proposes an innovative procedure for both objective and subjective validation and reports the results of its application to the DIMEG simulator. Fine tuning and validation activities were performed inside the 2BeSafe project in the Seventh European Framework Programme (theme 7 – sustainable surface transport), and commenced in January 2009. 2BeSafe is a collaborative research project and its objective is to conduct behavioural and ergonomic research in order to develop countermeasures for enhancing powered two-wheeler (PTW) riders' safety, including research into crash causes and human errors and the world's first naturalistic riding study involving instrumented PTWs.
This paper first describes the DIMEG simulator, then explains the proposed validation methodology and illustrates the data collected during objective and subjective evaluation.

2 DESCRIPTION OF THE RIDING SIMULATOR

A simulator is a complex system that aims to reproduce a real environment in a restricted and controlled area where it is possible to simulate any actions under totally safe conditions. The motorcycle riding simulator shown in Figure 1 is a top of the range one and has been designed and developed in its entirety at DIMEG. On the simulator, the rider sits on a motorcycle mock-up and operates the throttle position, brakes, clutch and gearshift lever like on a real bike. Moreover, the handlebar and footpads are sensorized.

The rider's control actions are transferred to the real-time multibody model of the motorcycle which has a 14 'degrees of freedom' model, includes a realistic model of the suspension, clutch, engine, tires and a 3-D road, and has been optimised for real-time performance. The simulated dynamics are then filtered by the washout and converted into references for the motion and vis-

Figure 1. The UNIPD riding simulator

ual cues. Motion cues are generated by the servomotors that drive 5 axes of the mock motorcycle; the roll, pitch, yaw and steer rotations plus the lateral displacement. The different subsystems are described in detail below.

2.1 Motorcycle mock-up

The rider rides a motorcycle mock-up equipped with all of the commands available on a real bike. In particular, the rider's actions are monitored by measuring the steering torque, leaning of the body, throttle position, front brake lever and rear brake pedal pressures, clutch position and gearshift lever position.
Figure 2 shows the motion cues of a motorcycle mock-up whose serial kinematic chain is composed of 4 mobile frames plus a fixed one to reproduce the motion of the vehicle in terms of lateral displacement, yaw, roll, pitch and steer rotations. The first mobile member has the yaw and lateral displacement degrees of freedom, which are actuated by two servomotors equipped with ball screws; in sequence there are the roll, the pitch and steer degrees of freedom, as summarised in Figure 2.
The simulator includes a audio-visual system; in particular, the scenario is projected onto three widescreens measuring 1.5 x 2m2 placed in front of the rider. The 5.1 surround sound system reproduces engine sound previously recorded on a real motorcycle for a range of engine rpm

Motion cue parameters	
Yaw	±20°, ±0.20°/s
Lateral motion	±0.3m, ±0.3m/s
Roll	±20°, ±60°/s
Pitch	±10°, ±50°/s
Steering	±20°, ±50°/s

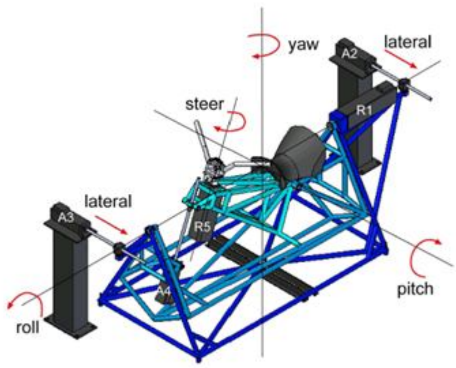

Figure 2. Motion cue capabilities of the UNIPD simulator

2.2 Real-time multibody model

In order to achieve a good, realistic correspondence between a real and the simulated motorcycle a detailed multibody model was developed.
The motorcycle model is composed of a whole motorcycle; its front frame, wheels and the rider's upper body (see Figure 3).
The mathematical model is non linear and has 14 DOF (Figure 3), corresponding to the position and orientation of the chassis, the steering angle, the front and rear suspension travels, the front and rear wheel rotations, the engine spin rate, the front fork bending deflection and the sprocket

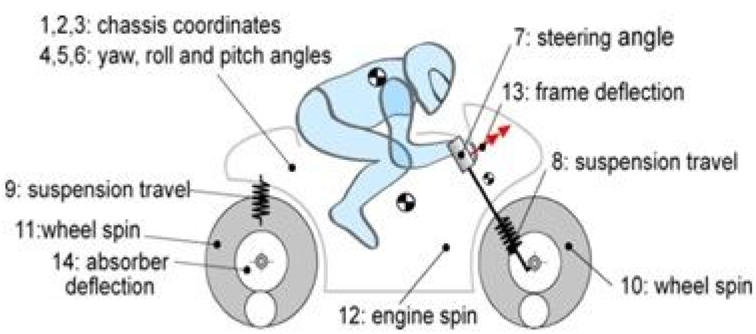

Figure 3. Virtual motorcycle model

absorber deflection. There are 7 motorcycle inputs: steering torque, throttle position, rear and front brake torques, gears selected, clutch position and the foot pegs effort (as an indirect measure of the rider's torso motion). Suspensions and tires are modelled in detail, as well as the clutch, the gearbox and the engine. More details are given in references [9]-[10].

2.3 Washout filter

Since it is physically impossible to reproduce accelerations as they are in real life using the simulator, a washout filter is used, which aims to recreate riding accelerations and angular velocities by using the acceleration and the angular velocity of the simulator (inertial effect) and the acceleration of gravity (gravitational effect). Simulated accelerations are first separated by filters into their spectral components. The components at low frequencies are generated using the gravitational effect, slowly tilting the simulator, while the components at high frequencies are reproduced by moving the simulator faster (with the electrical engine) and exploiting the effects generated by the inertial motion. As shown in Figure 4**,** this implemented washout is made up of two parts: the first filter (low pass filter), after an initial gauge, which removes high frequency components of input variables and includes a matrix that combines the various inputs in a linear combination, and, after that, a second filter which provides the output for the platform.

It has been found that moving the simulator like a real motorcycle to the greatest possible extent does not give the best riding feeling, so gains and other adjustable parameters of the washout filter have been tuned using a trial-and-error procedure based on the subjective evaluation of feelings. Appropriate tuning leaded to a different washout for the visual and motion screens; as an example, while cornering, the roll angle is divided into two parts: the biggest one is used to tilt the virtual horizon on the screen, while a smaller part is used to give a motion cue by rolling the mock-up motorcycle. This solution is particularly useful while using the new visual system composed of three widescreens and a large field of view (FOV).

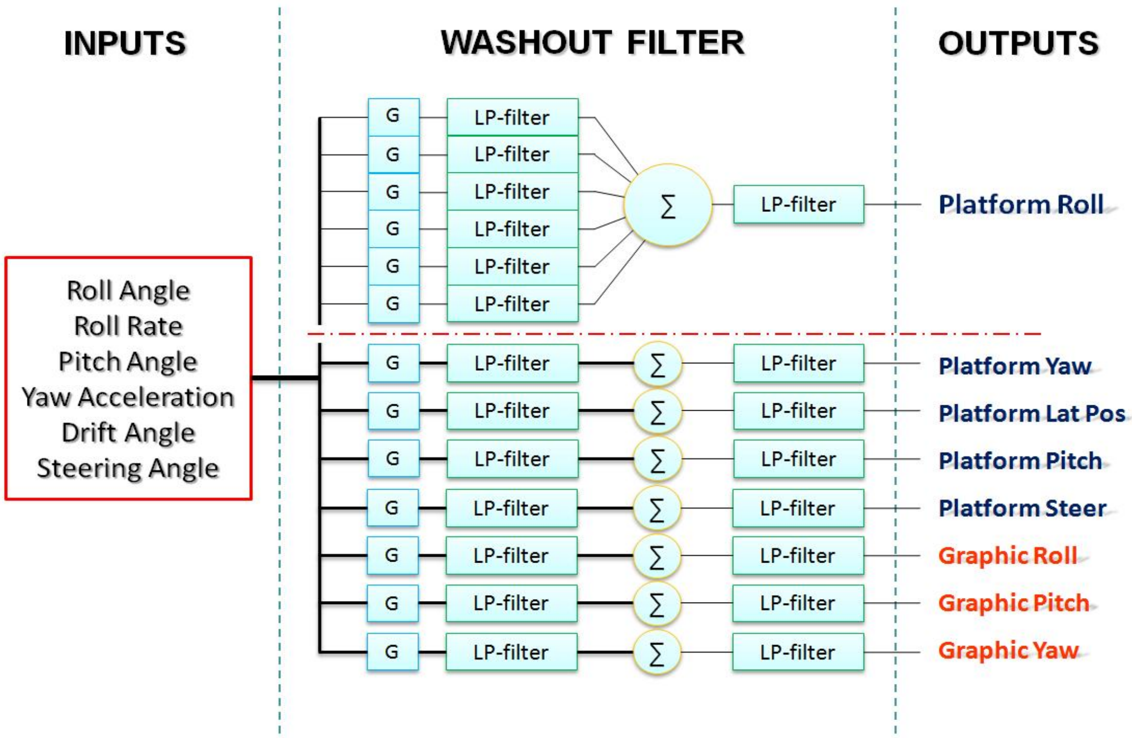

Figure 4. The washout filter architecture

3 SIMULATOR VALIDATION

3.1 Methodology

Motorcycle riding simulators are more recent than car and truck simulators, so they still need to be tuned to make them suitable for use in studies into rider behaviour. The challenge is to find an optimal compromise in the rendering of the simulator which allows the riders to feel as if they are riding an actual PTW and at the same time allows them to succeed in mastering the PTW as easily as they can master an actual one (at least for normal riding situations). To attain this goal, the following procedure has been iteratively applied: the first step is the fine-tuning of the motion, sound and visual rendering devices, which has been done experimentally using a small group of highly skilled riders; the second step is the simulator validation, conducted by comparing the behaviours, performances and self-reported impressions of a wider group of riders of different ages, experience and skill. The validation, which of course is the most important aspect, is based on two complementary concepts: the objective validation, where some objective, carefully selected parameters are compared between motorcycle and simulator test sessions and the subjective validation, where the riding feeling is evaluated by means of the subjective rating of test subjects.

The aim of the validation process may be better understood by looking at Figure 5. On the left, it shows the interaction between a rider and a motorcycle: the rider controls the motorcycle (by moving the handlebar, by actuating the throttle or by braking etc.), the result is the actual motion of the vehicle and then feedback is given to the rider in terms of motion, sounds and visual cues. On the right, it shows the interaction between a rider and a virtual motorcycle (i.e. a riding simulator) with the same kind of human-machine interaction as in real conditions.

Since it is physically impossible to reproduce accelerations as they are in real life using the simulator, it is fundamental to use a washout filter and properly tune it. The washout tuning has been carried out by team members who are also expert riders and engineers involved in motorcycle dynamics. Tuning was performed with particular attention to:

- the perception of the speed;
- the braking feeling and the feeling while riding on bumpy roads;
- the feeling during transient cornering;
- the vehicle responsiveness during lane changes, overtaking and obstacle avoidance manoeuvres;
- the riding experience at low speed.

Besides the identification of the most suitable washout filter parameters, the tuning phase demonstrated that foot pegs control is very important for the improvement of rider feeling in transient motion and that the projection system using 3 widescreens greatly improved speed perception, even if it did increase simulator sickness.

After the completion of tuning, a final validation was conducted using a sample group of riders of different ages and levels of experience and skill. This was done by considering both objective and subjective data, as explained in detail in the next sections.

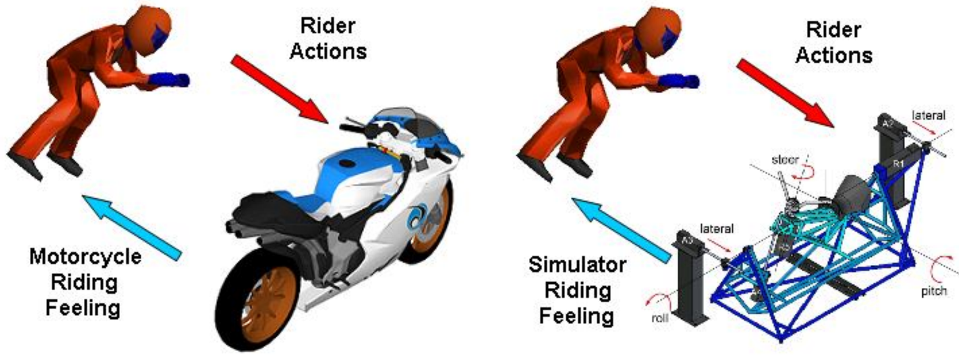

Figure 5. The rider-motorcycle interaction and the rider-simulator interaction

3.2 Objective evaluation

The objective evaluation consists of a comparison between the behaviour of the real and virtual motorcycles during the same riding actions. Despite the fact that there are many riding conditions with several uncontrolled parameters, the literature concerning the objective evaluation of motorcycle handling characteristics [8]-[27] helped us to focus on selected manoeuvres that are representative of the more general vehicle behaviour. In particular, the following three typical manoeuvres have been selected for the evaluation of the riding experience:

- Slalom (three different cone distances);
- Lane change (two different lane geometries);
- Steady turning (three radii);

The above manoeuvres are also part of the set of manoeuvres commonly used by motorcycle manufacturers to develop their own vehicles. Tests were carried out by two skilled riders. The motorcycle used for the tests was equipped with a special handlebar with steering torque and steering angle sensor, foot pegs with load cells, GPS and an inertial measurement unit with accelerometers and gyrometers.

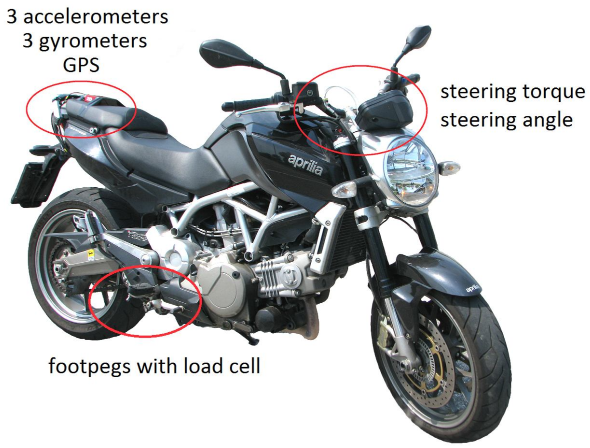

Figure 6. The UNIPD instrumented motorcycle

The slalom test was performed with three different distances between the cones on a straight line at established speeds. For the sake of clarity, the results of both the simulator and motorcycle tests are presented in Table 1, indicating the most relevant parameters. Since it is practically impossible to reproduce exactly the same manoeuvre, first on the motorcycle and then on the simulator, the comparison between real and simulated manoeuvres is more meaningful when based on the ratio Gx/τ between the roll rate (which represents the vehicle behaviour) and the steering torque (which represents the rider action). Moreover, the ratio Gx/Gz between the roll and yaw rates and the phase lag $\varphi_1 - \varphi_2$ between the Gx phase and the steering torque gives additional information. As the cone distance increases from 14m to 21m the magnitude ratio decreases, whereas there are only small changes in the phase difference. This can be observed from the values in Table 1.

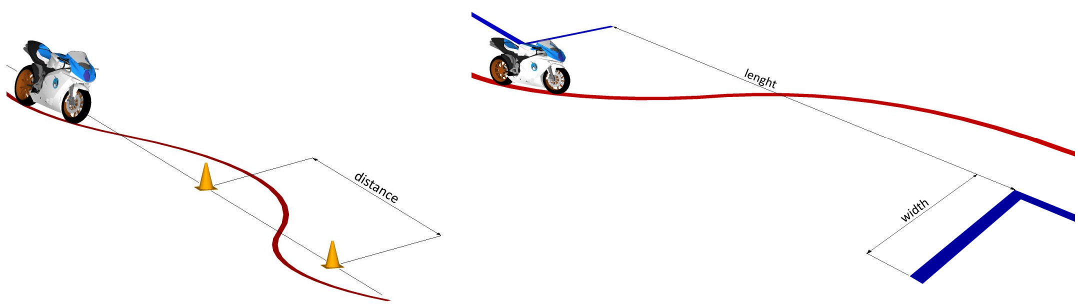

Figure 7. Slalom and Lane Change geometric characteristics

Table 1. Slalom indices: comparison between motorcycle and simulator

	Slalom													
Cones	**7m**				**14m**						**21m**			
	Aprilia Mana 850		**UNIPD SIMULATOR**		**Aprilia Mana 850**		**UNIPD SIMULATOR**		**UNIPD SIMULATOR**		**Aprilia Mana 850**		**UNIPD SIMULATOR**	
Frequency [Hz]	0.3463		0.3393		0.4474		0.3557		0.3604		0.4548		0.3581	
Av. speed [m/s]	4.8483		4.7505		12.5261		9.9588		10.0917		19.1029		15.0382	
	magn	phase	magn	phase	magn	phase	magn	phase	magn	phase	magn	phase	magn	phase
Gx [°/s]	0.462	3.356	0.430	0.236	1.243	2.254	0.587	3.499	0.569	2.997	1.188	0.328	0.753	6.094
Gz [°/s]	0.522	5.145	0.466	2.399	0.473	4.242	0.271	5.386	0.288	4.911	0.310	2.446	0.255	1.638
Steer Torque [Nm]	12.946	2.192	16.660	3.061	27.836	5.502	19.701	0.165	18.344	5.909	45.300	3.425	29.384	2.796
Steer angle [°]	0.167	5.026	0.138	2.448	0.053	4.050	0.043	5.456	0.051	4.962	0.041	2.537	0.029	1.794
Gx/τ	**0.0357**		**0.0258**		**0.0446**		**0.0298**		**0.0310**		**0.0262**		**0.0256**	
Gx/Gz	0.8849		0.9239		2.6274		2.1682		1.9784		3.8280		2.9487	
$\varphi_1-\varphi_2$	-1.1647		-2.8252		-3.2484		-3.3336		-2.9124		-3.0974		-3.2986	

Lane change manoeuvres may be classified by means of the width and length of the trajectory and vehicle speed, as shown in Figure 7. In this case, tests have been performed using a lane width of 3m and lengths of 14 and 21m at speed range between 50 and 75km/h. The manoeuvre can start from the right side and finish on the left side of the cones (right to left lane change) or the reverse. In addition, in this situation the speed should be kept constant as much as possible.
In the lane change manoeuvre the rider exerts some controlling action (torque) causing the vehi-

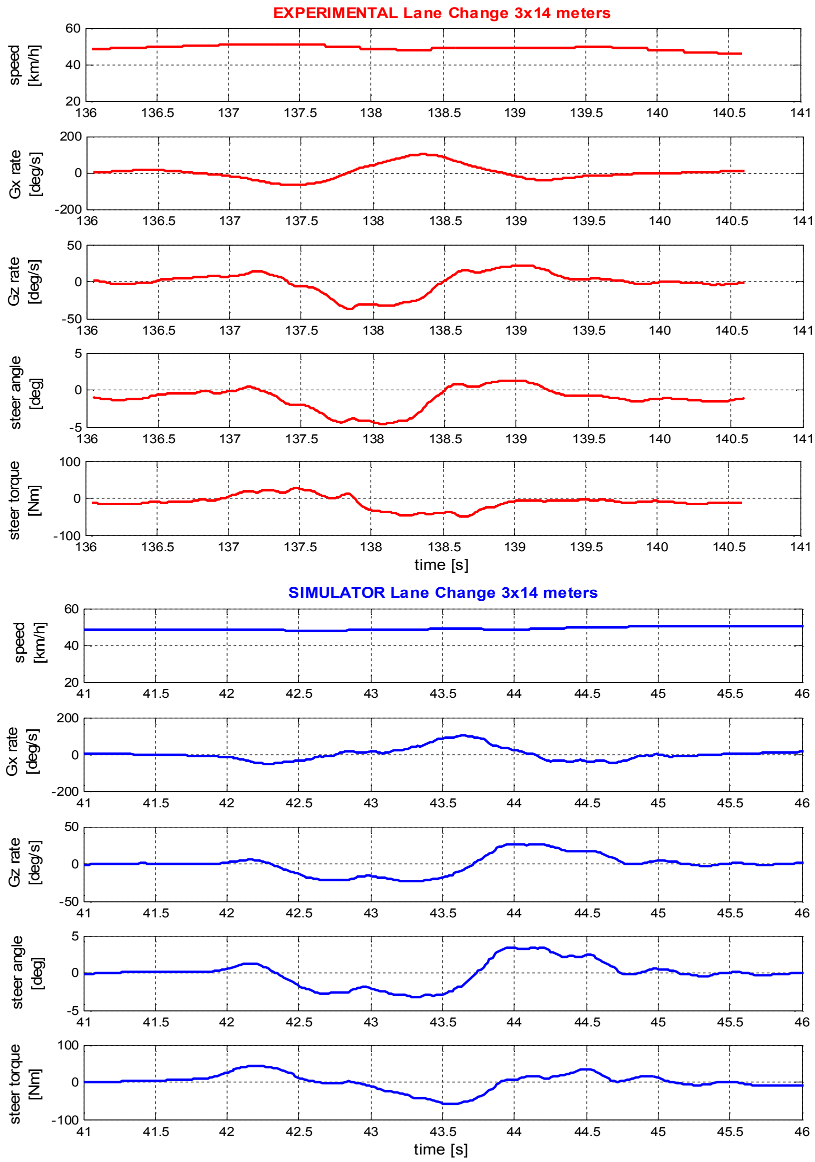

Figure 8. Lane change manoeuvre: comparison between experimental and simulation manoeuvres

cle to roll and yaw. The ratio of the peak-to-peak magnitude of steering torque to the peak-to-peak roll rate is a good indicator of a motorcycle's manoeuvrability. Normalising this quantity by velocity we obtain the lane change roll (LCR) index, where the subscript p-p indicates peak-to-peak values [6], [12], [15], [16], [25]:

$$Lane\,Change\,Roll\,Index = \frac{\tau_{p-p}}{\dot{\varphi}_{p-p} \cdot V_{avg}}$$

This index represents the effort required on the part of the rider in the form of steering torque to obtain a desired vehicle response in roll rate and can be used to contrast the behaviour of different classes of motorcycle: touring, sport, cruiser etc. Results of the simulator and motorcycle tests are compared in Table 2 where the range of the values for each parameter during the test is presented. This has been done in order to calculate the lane change roll index explained above and the data have been collected in Table 2 under the name MDRG Index. There are some differences in the index value, more so in the 3 x 14m test than the 3 x 21m test, but both indices are comparable with the typical value of the LCR index.

Table 2. Lane change indices: comparison between motorcycle and simulator

	Lane Change			
Cones	**3x14**		**3x21**	
	Aprilia Mana 850	**UNIPD SIMULATOR**	**Aprilia Mana 850**	**UNIPD SIMULATOR**
Speed [km/h]	49.12	49.01	55.25	58.29
G_{xmax} [°/s]	100.70	102.00	90.50	39.87
G_{xmin} [°/s]	-64.10	-52.20	-63.10	-103.30
ΔG_x [°/s]	164.80	154.20	153.60	143.17
G_{zmax} [°/s]	22.30	26.64	21.90	18.95
G_{zmin} [°/s]	-36.70	-23.54	-31.90	-16.85
ΔG_z [°/s]	59.00	50.18	53.80	35.80
δ_{max} [°]	1.30	3.35	3.20	1.75
δ_{min} [°]	-4.60	-3.27	-1.60	-1.05
$\Delta\delta$ [°]	5.90	6.62	4.80	2.80
τ_{max} [Nm]	28.21	42.91	52.10	64.84
τ_{min} [Nm]	-50.40	-59.29	-31.94	-41.96
$\Delta\tau$ [Nm]	78.61	102.20	84.04	106.80
MDRG index	2.0042	2.7907	2.0436	2.6409

The steady state circular test (riding at a constant speed on a circular path, see Figure 9) was conducted with different turning radii . For each test, the acceleration index [12], [15], [16], [26], [27] has been calculated, which is a manoeuvrability index that links the riding parameters as follows:

$$Acceleration\;\;Index = \frac{\tau}{\bar{v}^2 / R_c}$$

Where τ is the steering torque, $\bar{v}$ is the average speed [m/s] and R_c is the cornering radius. According to the literature [19], the relationship between driver action and vehicle response can be quantified using the ratio between the steering torque and lateral acceleration, as shown above. The acceleration index is mainly negative (i.e. negative steering torque, outwards of the curve) and characteristically, for a given radius, it transitions from negative to positive (i.e. positive steering torque, towards the curve) as speed increases. Negative applied steering torque is preferable because in this situation the motorcycle's tuning behaviour tends to be stable. Simulator and motorcycle test results are collected in Table 3. For each parameter, the average has been calculated to obtain the acceleration index explained above. In Table 3, the value of the negative radii corresponds to a counter-clockwise manoeuvre. The magnitude is always comparable with the typical value of the acceleration index calculated on different motorcycles [26]-[27].

Table 3. Steady state circular test indices: comparison between motorcycle and simulator

	Steady Turning					
Radius [m]	-10		-17		-25	
	Aprilia Mana 850	**UNIPD SIMULATOR**	**Aprilia Mana 850**	**UNIPD SIMULATOR**	**Aprilia Mana 850**	**UNIPD SIMULATOR**
av_speed	32.74	26.05	36.10	28.57	36.97	33.83
av_Gx	-2.29	-0.51	-2.04	0.02	-1.40	0.12
av_Gz	-27.42	-35.56	-25.39	-25.92	-22.77	-21.02
av_δ	-5.44	-8.93	-4.76	-5.64	-4.36	-3.76
av_τ	13.66	18.13	12.86	8.08	11.25	6.61
acceleration index	**-1.65**	**-3.46**	**-2.17**	**-2.18**	**-2.67**	**-1.87**

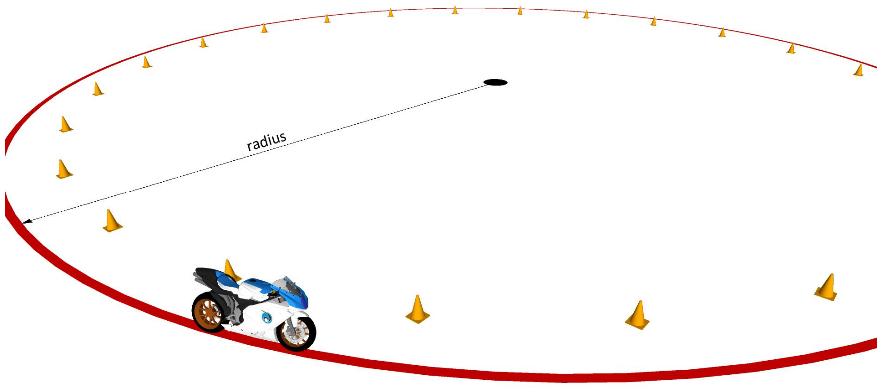

Figure 9. Steady state manoeuvre

3.3 Subjective evaluation

3.3.1 *Test protocol*

This section explain the procedures adopted for the improvement done with Tuning and the results collected with the Subjective evaluation. The riding sensations of the test riders have been collected by means of a questionnaire, which includes both technical questions and questions about perception and cognitive processes.

The questionnaire focuses on different aspects and situations including speed perception, the feeling accompanying braking and acceleration, the feelings of cornering and overtaking and obstacle avoidance. Moreover, for each situation is rated the fidelity of the simulator response to the rider input, the motion cues (in particular roll motion feeling and longitudinal acceleration feeling), and the audio/visual cues.

While a group of 2-3 expert riders may be reasonably a good solution for the simulator tuning, the final validation and in particular the Subjective evaluation have to be conducted on a wider user group of at least 10 subjects, with an age range in the 20-60 year, with different riding experience but a minimum of 2000 km per year and holders of a valid riding license for at least 2 years, and with the presence of some high experienced rider (to avoid special biases induced by inexperience, problems with learning and becoming familiar with the equipment etc).

Tests are carried out according the following protocol:

1. Each participant fill the Participant Profile questionnaire where are collected the general information of the rider .
2. The experimenter explain the participant how the simulator works and in particular how he/she should ride on the simulator.

3. The test starts with a warm up phase in order to make the participant confident with the simulator command: handlebar, brakes and clutch. In this phase the experimenter will ask the participant to make some simple, specific task (see Annex) on a (virtual) free space. The warm up duration is approximately 8-10 minutes.
4. The warm up is followed by the rural naturalistic riding, i.e. the participant has to ride in a (virtual) rural environment for 8-10 minutes, with low traffic conditions.
5. The last phase is the urban naturalistic riding, i.e. the participant has to ride in a (virtual) urban environment for 8-10 minutes, with normal traffic conditions.
6. After simulator riding, the participant has to fill the Rider Feeling Questionnaire as described above.

3.3.2 *Tuning*

The washout tuning has been carried out by two team members that are not only very expert rider, but also expert engineers involved in motorcycle dynamics.
In the original configuration the UNIPD simulator was equipped with only one widescreen and only the handlebar was used for the lateral control of the motorcycle, even if it was already planned to design and install the foot pegs control. The initial rating of riding feeling is depicted in Figure 10, in particular it has been considered essential to improve the following riding sensations:

- the perception of the speed;
- the braking feeling, feeling while riding on bumped roads;
- the feeling during transient cornering;
- the vehicle promptness during lane change, overtake and obstacle avoidance manoeuvres;
- the riding feeling at low speed.

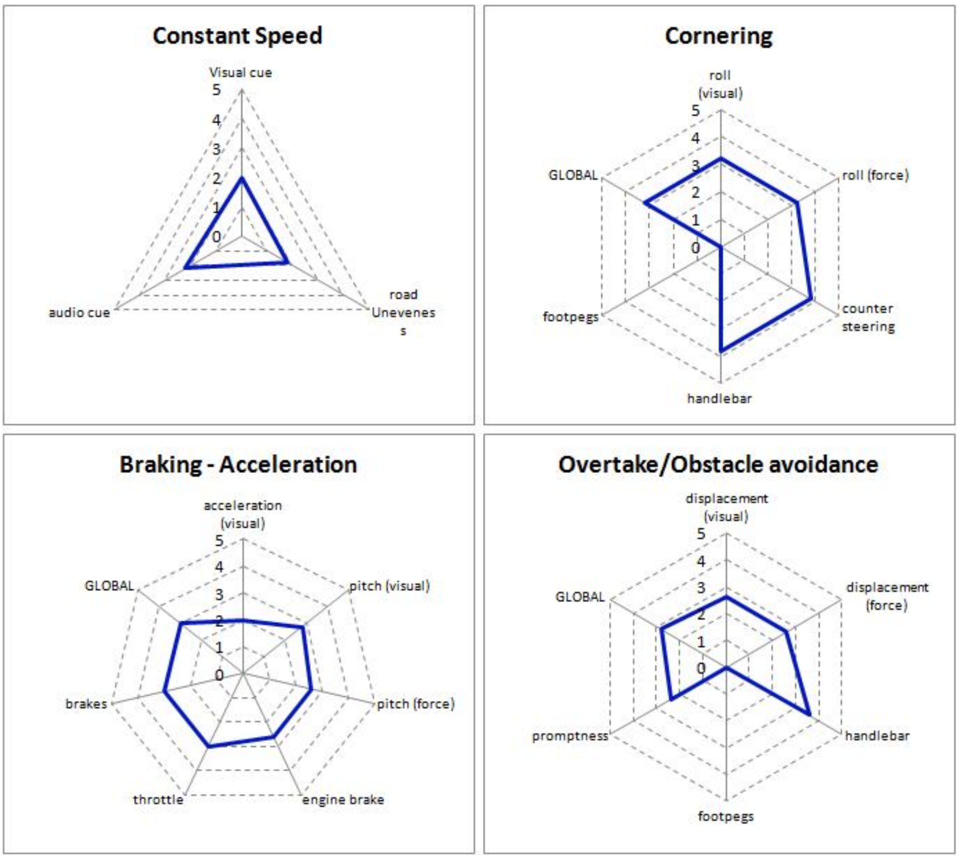

Figure 10. Rating of simulator riding feeling: starting project conditions

3.3.3 *Final validation*

The simulator validation has been conducted on a test sample of 12 people (9 males plus 3 females), with riding experience in accordance with specifications on section 1. As the Full Features Setup arises to be the preferred by users, it has been decided to increase the number of testers to 20 people (17 males plus 3 females) for a better quality of the results.
Three different simulator setups have been tested:

- **Full Features**: the final setup of fine tuning, which include the three screens system, the foot pegs control and optimized washout;
- **Handlebar w/o Foot pegs**: the first setup without the foot peg control, to verify that the foot peg control is perceived as a natural way of riding, even if the implemented system does not perfectly reproduce the physics of rider leaning.
- **Single Screen**: the setup above with only one screen, which has been selected to verify if the improvement in the perception of speed is not vanished by the (limited) increment of simulator sickness.

In Figure 11 are collected and compared the average rating for different setups tested.

The aim of subjective evaluation is the enhancement of riding sensations in terms of visuals, acoustics and motion cues. It is worth highlighting that each different kind of cue has different physical and technological limitations; in particular, for visual cues there are limitations due to the need to stay true to the scenario being represented, as well as technological limitations in terms of resolution and the brightness capabilities of the visual devices. For acoustic cues there are technological limitations in the reproduction of the sound and noises of the environment; for motion cues there are both technological and (more problematic) physical limitations; indeed, the reproduction of acceleration is partial in amplitude and duration since the travel of the motorcycle mock-up is limited. Further limitations on the acceleration frequency bandwidth depend on the power of the simulator motor.

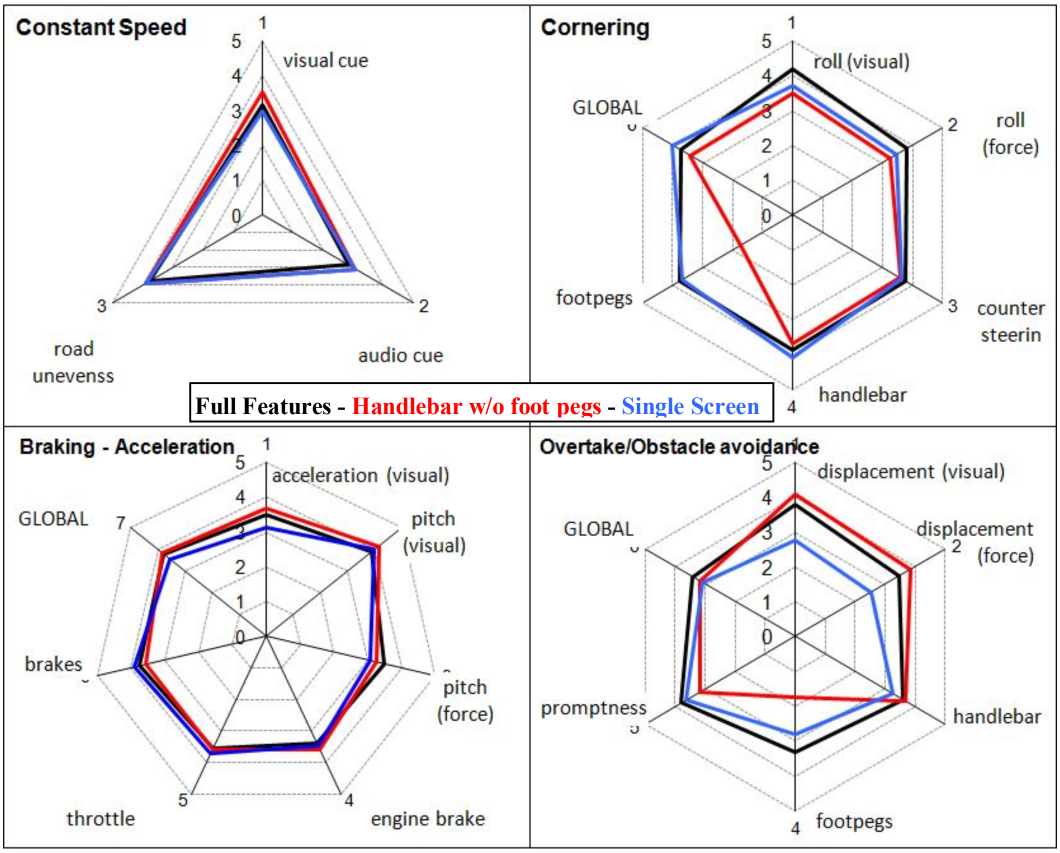

Figure 11. Simulator Rating for all tested configuration

4 CONCLUSION

The paper has presented the main features of the motorcycle riding simulator developed by the University of Padova, proposed a method for the objective and subjective evaluation of simulator riding feeling and presented the results of the validation of the DIMEG simulator conducted using a group of 20 riders of different levels of experience. The tests outlined have been done inside the 2BeSafe project in the Seventh European Framework Programme (theme 7 – sustainable surface transport), and commenced in January 2009. 2BeSafe is a collaborative research project and its objective is to conduct behavioural and ergonomic research in order to develop countermeasures for enhancing the safety of powered two wheeler (PTW) riders. This has included research into crash causes and human errors, and the world's first naturalistic riding study involving instrumented PTWs.

Objective validation demonstrated that the DIMEG motorcycle simulator reproduces with good approximation the physics of a real motorcycle. Subjective validation showed that, at the end of a trial and error tuning procedure, the audio visual experience and feelings of movement perceived by the rider had been remarkable increased. In particular, the riding experience has been improved by the installation of the visual system using three widescreens and the introduction of foot peg control.

ACKNOWLEDGMENT

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REFERENCES

[1] Chiyoda S, Yoshimoto K., Kawasaki D, Murakami Y, Sugimoto T (2000) Development of a motorcycle simulator using parallel manipulator and head mounted display. Driving Simulator Conference, DSC 2000, Paris, France, September 6-7

[2] Miyamaru Y, Yamasaky G, Aoky K (2002) Development of motorcycle riding simulator. JSAE Review 23:121-126

[3] Cossalter V, Lot R., Doria A (2003) Sviluppo di un simulatore di guida motociclistico. Proc. of the 16th AIMETA Congress of Theoretical and Applied Mechanics, Ferrara, Italy, September 9-12 2003

[4] Ferrazzin D, Barbagli F, Avizzano C, Pietro G, Bergamasco M (2003) Designing new commercial motorcycles through a highly reconfigurable virtual reality-based simulator. Journal of Advanced Robotics 17:4:293-318

[5] Nehaoua L, Hima S, Arioui H., Seguy N, Éspié S (2007) Design and modelling of a new motorcycle riding simulator. Proc. of the American Control Conference, New York City, USA, July 11-13 2007

[6] Cossalter V, Lot R, Sartori R, Massaro R, A motorcycle riding simulator for the improvement of the rider safety. FISITA F 2008-11-015

[7] Cossalter V, Lot R, Doria A, Maso M (2006) A motorcycle riding simulator for assessing the riding ability and for testing rider assistance systems. 9th Driving Simulation Conference, Paris, France, October 4-6 2006

[8] Cossalter V, Doria A, Lot R (2004) Development and validation of a motorcycle riding simulator. FISITA, Barcelona, May 2004

[9] Cossalter V, Lot R, A motorcycle multi-body model for real time simulations based on the natural coordinates approach. Vehicle System Dynamics 37:6:423-448

[10] Cossalter V, Lot R, Maggio F (2003) A multibody code for motorcycle handling and stability analysis with validation and examples of application. Small Engine Technology Conference & Exhibition, Madison, WI, USA, September 2003, SAE 2003-32-0035 / 20034335

[11] Koch J (1978) Experimentelle und analytische untersuchungen des motorrad-fahrer systems. Dissertation, Berlin

[12] Zellner J, Weir D (1978) Development of handling test procedures for motorcycles. Warrendale, PA, SAE 780313

[13] Weir DH, Zellner JW (May 1979) Motorcycle handling - volume I: summary report. U.S. Department of Transportation, 001-05, DOT HS-804 190 MISC

[14] Weir DH, Zellner JW, Teper GL (My 1978) Motorcycle handling - volume II: technical report, U.S. Department of Transportation, No. 1086-1

[15] Rice RS (1978) Rider skill influences on motorcycle manoeuvring. Warrendale, PA, SAE 780312

[16] Kuroiwa O, Baba M, Nakata N (1995) Study of motorcycle handling characteristics and rider feeling during lane change. Warrendale, PA, SAE 950200

[17] Bunz D, Klasen M, Schaffler A (2004) Determination of parameters for objective evaluation of motorcycles driving dynamics behaviour. 5th International Motorcycle Conference, Munich, Germany, Sept 2004

[18] Varat M, Husher S, Shuman K, Kerkhoff J (2004) Rider inputs and powered two wheeler response for pre-crash manoeuvres. Proceedings of the 2004 International Motorcycle Safety Conference (Institut Fur Zweiradsicherheit e.v., Munich, Germany)

[19] Cossalter V (2002) Motorcycle dynamics. Race Dynamics, Greendale, WI

[20] Sharp R (1997) Design for good motorcycle handling qualities. Warrendale, PA, SAE972124

[21] Cossalter V, Da Lio M, Lot R, Fabbri L (1999) A general method for the evaluation of vehicle manoeuvrability with special emphasis on motorcycles. Vehicle System Dynamics 31:2:113-135

[22] Roe GE, Thorpe TE (1980) Improvements to the stability, handling, and braking of high-performance motorcycles. Motorcycle Safety Foundation Int. Conference, Washington Proceedings, 565-597

[23] Schweers TF, Remde D (1993) Objective assessment of motorcycle manoeuvrability. Warrendale, PA, SAE 950200

[24] Cossalter V, Lot R, Doria A, Maso M (2006) A motorcycle riding simulator for assessing the riding ability and for testing rider assistance systems. 9th Driving Simulation Conference, Paris, France, October 4-6 2006

[25] Sadauckas J, Cossalter V (2006) Elaboration and quantitative assessment of manoeuvrability for motorcycle lane change. Vehicle System Dynamics: International Journal of Vehicle Mechanics and Mobility 44:12:903-920 ISSN 0042-3114

[26] Cossalter V, Lot R, Peretto M (2007) Motorcycles steady turning. Journal of Automobile Engineering 221:Part D:1343-1356

[27] Cossalter V, Doria A, Lot R (March 1999) Steady turning of two wheeled vehicles. Vehicle System Dynamics 31:3:157-181.